Oceanus

REPORTS ON RESEARCH FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

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Catching the Rain

Particle Flux in the World Ocean

A sediment trap is lowered into the water to take its place on a mooring line, where it will collect 6 to 12 months' worth of particles descending through the water column in discrete samples that represent time periods ranging from several days to a month each. More than 280 such instruments are deployed around the world by investigators who represent a variety of research institutions and who are all contributing to understanding of Earth's biogeochemical cycles. See pages 8 to 10 for more information on sediment traps.

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Catching the Rain

Cover: ***Inset***—Steve Manganini (black shirt) directs deployment of a sediment trap mooring in the Arabian Sea in 1995. ***Background***—The scanning electron microscope preparation process dehydrated the organic material contained in a planktonic fecal pellet collected in the North Atlantic so that only the calcite coccoliths it contained can be seen. (Compare with the page 6 transmission electron microscope image of a fecal pellet that was collected by the same sediment trap but where organic material is preserved.) Area of photo is 25 x 35 micrometers.

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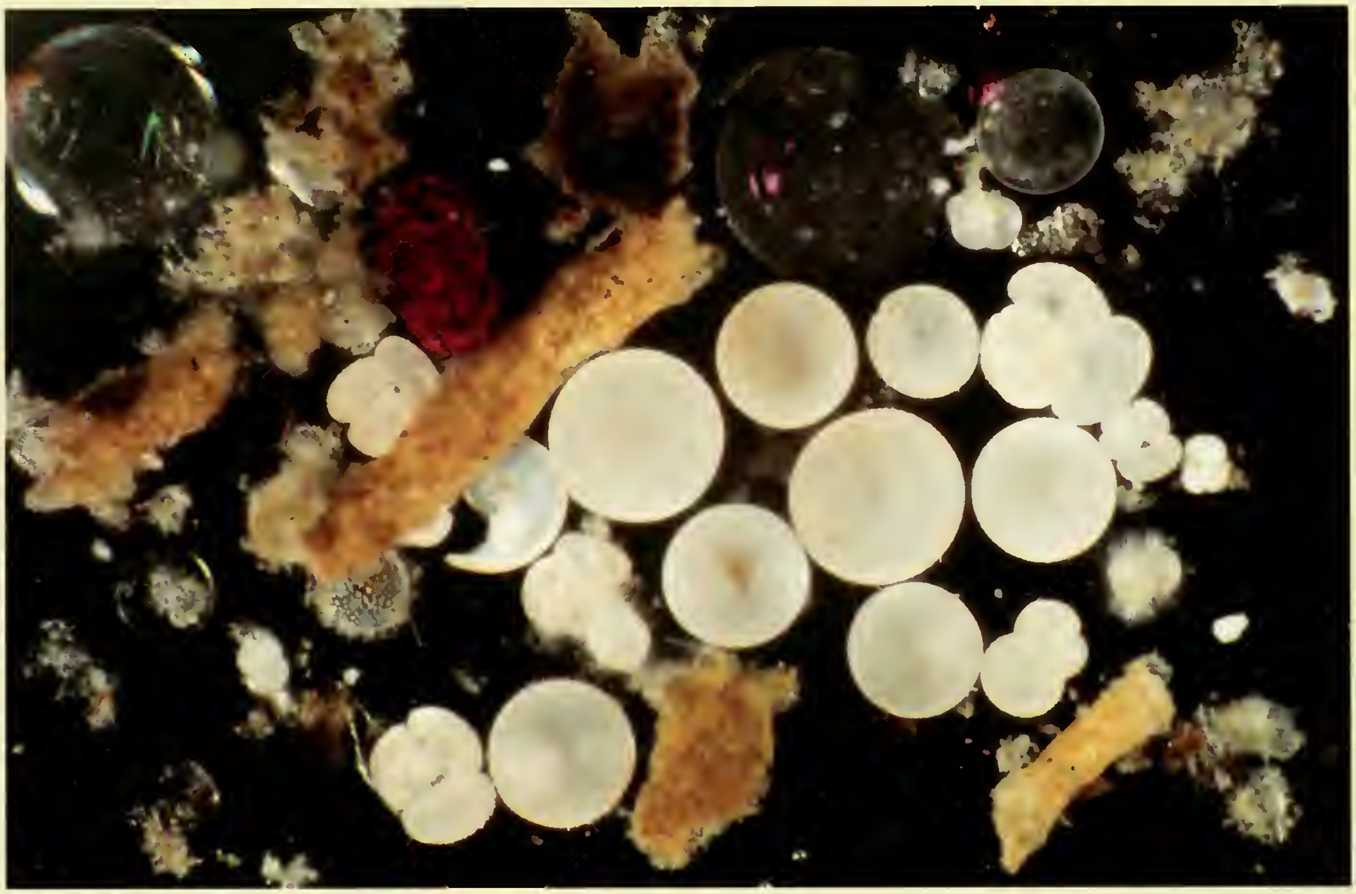


Susumu Honjo (Area of photo is 1.1 x 1.5 millimeters.)

One of the first photographs of a sediment trap sample shows cylindrical fecal pellets and other aggregates, planktonic tests (round white objects), transparent snail-like pteropod shells, radiolarians, and diatoms. The first deep-sea sediment trap was recovered on February 20, 1977, from 5,367 meters on the Sohm Abyssal Plain in the Sargasso Sea. As Sus Honjo and colleagues viewed the samples under a microscope, they confirmed a theory and began to solve the mystery of how benthic animals receive nourishment from surface waters in "packages" that descend through the water column.

Marine Snow and Fecal Pellets: The Spring Rain of Food to the Abyss

Until about 130 years ago, scholars believed that no life could exist in the deep ocean. The abyss was simply too dark and cold to sustain life. The discovery of many animals living in the abyssal environment by Sir Charles Wyville Thompson during HMS *Challenger's* 1872–1876 circumnavigation stunned the late 19th century scientific community far more than we can now imagine.

Major questions immediately emerged: How do deep sea animals obtain food so far from the ocean's surface where plants, the base of the ecosystem, grow? Do they all just wait until a whale corpse is occasionally delivered to the abyss? These questions were only answered fairly recently.

Twentieth century progress in oceanography resulted in further confusion. Microscopic particles suspended in the water column seemed so small and light that it was believed they should take hundreds, perhaps thousands, of years to settle through the water column. And what happens to labile (unstable) matter, particularly organic particles from dead, broken plankton cells? Scientists could not understand why coccoliths, the delicately architectured calcite shells of phytoplankton, only several micrometers in size, were preserved on the deep ocean floor just beneath the area where they were produced. Why were they not carried far from their source by currents, and how could they even exist there when chemistry clearly indicates they should be dissolved during their several-century trip to the bottom?

A WHOI experiment in the deep Sargasso Sea two decades ago shed light on this century-old question. Shipboard observation of the first successfully recovered sediment trap samples from 5 kilometers deep revealed that particles originating in the euphotic (light) zone aggregate: The fine, light particles do not settle individually but are repackaged into larger particles that settle to the deep sea at a much greater speed. Among the Sargasso Sea aggregates, we found an abundance of fecal pellets from upper ocean zooplankton. Viewing one of the fecal pellets under an electron microscope, I was fascinated to find it full of perfectly preserved coccoliths and undigested, many-celled organelles. Some oil droplets were obviously much lighter than seawater!

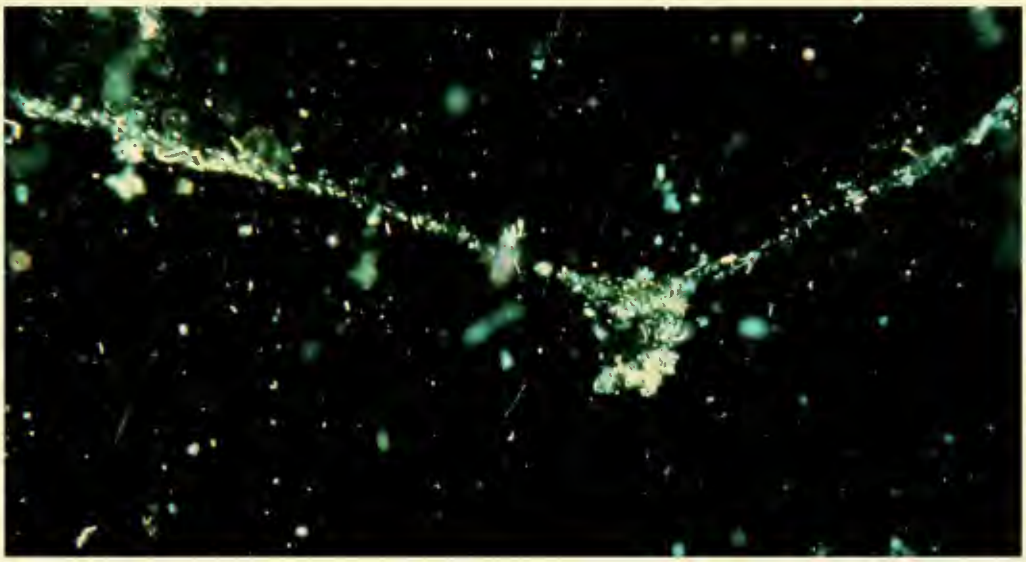
Because filter-feeding zooplankton are concerned only with the size of their food and graze phytoplankton almost indiscriminately, indigestible coccoliths and diatom frustules are concentrated in their fecal pellets. Many zooplankton fecal pellets are covered with a thin coating material. Although individual particles sink very slowly or are even buoyant, when they are bundled into a tight package and ballasted with particles of calcite—one of the densest materials produced in the ocean—they sink as rapidly as 100 to 200 meters a day.

Soon after World War II, scientists at Hokkaido University built an early submersible, named Kuroshio, to dive in the ocean north of Japan. Wherever they beamed a search light, they saw "snowflakes" dancing from the disturbance caused by the submersible. K. Kato and N. Suzuki named this phenomenon "marine snow." More recently, the author and former MIT/WHOI Joint Program student Vernon Asper, now at the University of Southern Mississippi, have worked with WHOI engineers to construct an optical instrument to measure the size and density of marine snow all the way down through the water column. Cindy Pilskaln, who did her Ph.D. research at WHOI while a Harvard University Student and is now at the University of Maine, has found that fecal pellets alone cannot transport the amount of organic carbon known to exist in the deep ocean, and that the density of suspended particles in the water column remains at a steady state. One hypothesis is that the vertical transport mechanism may be the combination of rapidly descending fecal pellets and aggregates as well as individually settling, relatively large particles such as planktonic foraminifera and diatoms. All of these together form "marine snow."

Many marine snow "flakes" are sticky and fibrous like a crumbled spider net, and particles easily adhere to them, forming agregates. An aggregate begins to sink when it attracts fecal pellets, foraminifera tests, airborne dust, and other heavier particles. As it descends, more suspended particles are added, making the aggregate even heavier and thus faster moving. An aggregate may break apart, spilling its contents into the water, but soon the spilled particles are picked up or "scavenged" by other falling aggregates. Thus aggregates are reorganized constantly with individual particles jumping on and off them before they arrive on the ocean floor. Meanwhile, a large portion of the organic matter in marine snow is recycled by microorganisms and upper and middle water column animals who again generate fecal pellets.

The removal of carbon from the ocean's euphotic layer to its interior carbon "sink" is critical to the process that keeps Earth's carbon cycle in order. We have learned that the speed of carbon settling to the ocean's interior is very rapid: Particles can travel from surface waters to the abyss in only a few days or weeks (see Arabian Sea article on page 24). Nature accomplishes this process ingeniously by wrapping labile organic carbon up in a package and ballasting it with calcium carbonate, which causes it to settle at high speed to the deep ocean environment.

Sir Charles Wyville Thompson would have been happy to know this! *—Sus Honjo*



Susumu Honjo

A component of "marine snow" was captured at 55 meters in Monterey Bay, California, by a light scattering optical device that also counts and estimates the size of individual particles contained in a cubic meter of water. The view includes individually settling fecal pellets as well as amorphous aggregates that look like white flakes, which are a half to several millimeters in diameter and often host a large number of fecal pellets. Zooplankton produce the weblike material that helps agglutinate particles to form aggregates.

The Rain of Ocean Particles and Earth's Carbon Cycle

Susumu Honjo
Senior Scientist, Geology and Geophysics Department

Phytoplankton photosynthesis has provided Earth's inhabitants with oxygen since early life began. Without this process the atmosphere would consist of carbon dioxide (CO_2) plus a small amount of nitrogen, the atmospheric pressure would be 60 times higher than the air we breathe, and the planet's air temperatures would hover around 300°C. (Conditions similar to these are found on Earth's close sibling Venus).

As phytoplankton grow through the process of photosynthesis, they fix CO_2 in their cells as organic carbon and thus absorb atmospheric CO_2 into the upper ocean layers. Animal plankton graze the phytoplankton, employing most of the organic carbon as their energy source and oxidizing the rest of it back to CO_2, which eventually returns to the atmosphere. A small portion of this photosynthetic carbon escapes the oxidation process by settling, or "sedimenting," through the water column in particles, which are often called "marine snow" and include pelletized feces of small animal plankton. CO_2 carbon is also transported to the deep ocean in another way: Some plankton, such as coccolithophorids, planktonic foraminifera, and pteropods produce beautiful calcite and aragonite shells or tests that sink toward the seafloor when the organisms die.

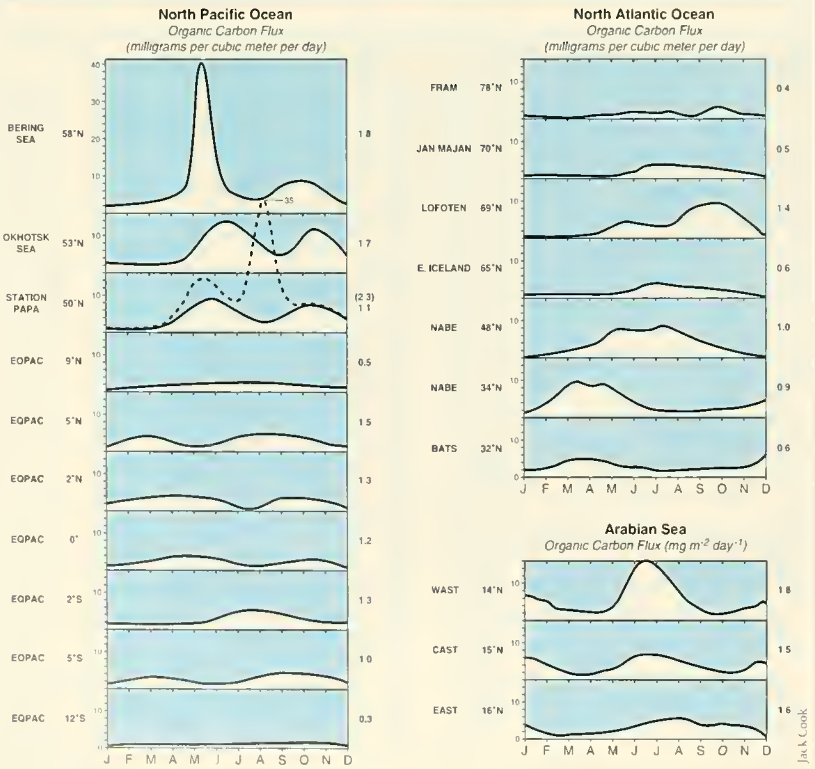
Once the organic carbon and calcium carbonate particles reach the ocean interior at a depth of a few kilometers, they are "stored" there and will not return to the atmosphere for a relatively long period of time. This complex carbon-transporting ocean process, often called the "biological pump," is a critical mechanism in preventing what we now know as the "greenhouse effect," the collection of gases in the atmosphere that hinders upward transport of heat.

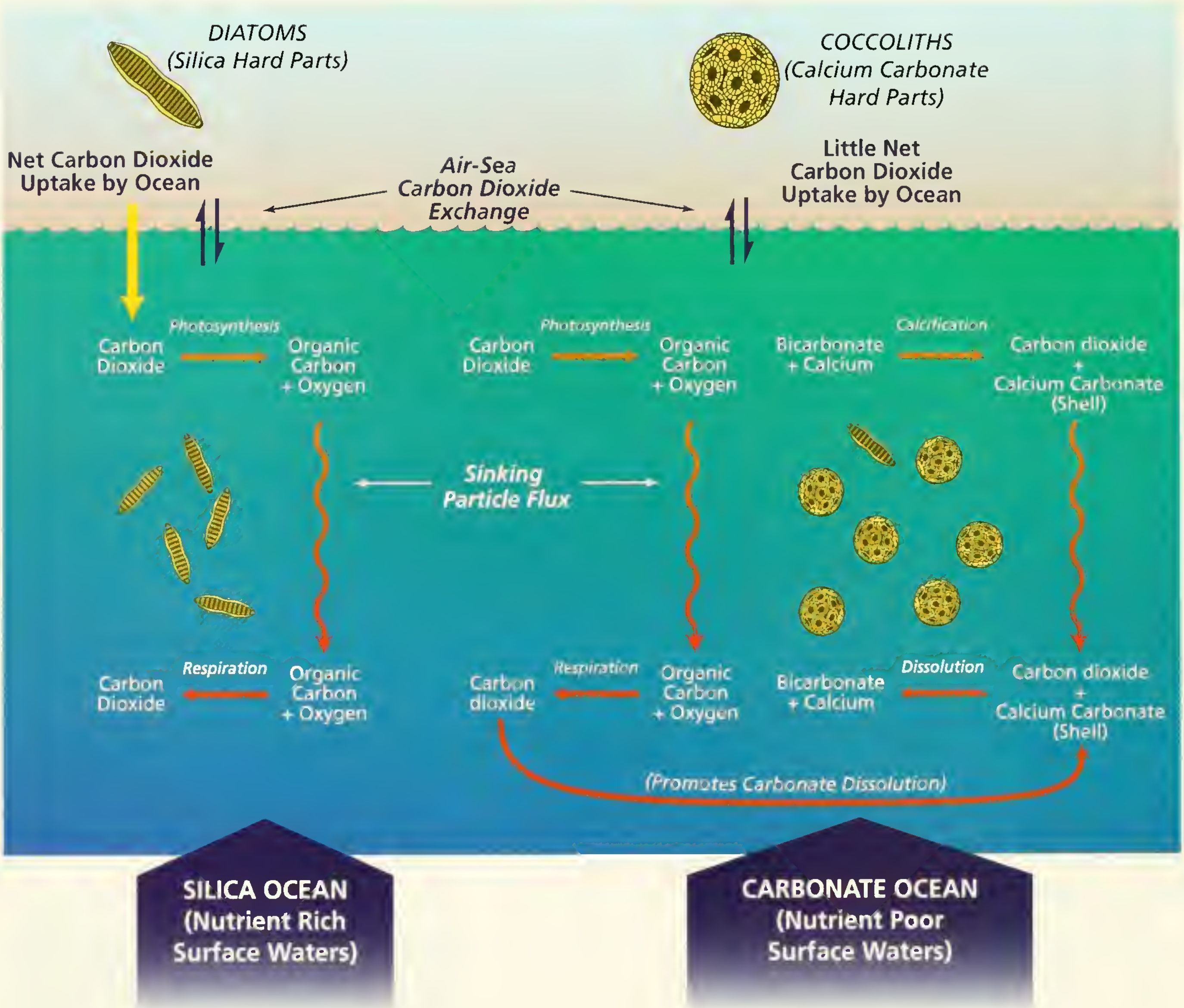
Understanding of Earth's carbon cycle is one of humankind's great scientific questions. Sediment traps are an important tool for studying the spatial and temporal variability of sinking particles (and carbon) in the ocean. The idea behind these devices is very simple: Vertically settling particles are collected at a specific area during a specific time period by providing a stable collection area at a depth along a mooring. The collected particles are then recovered and weighed, and the vertical flux of particles can be calculated as weight or volume per unit area in a unit of time—milligrams per square meter per day. Because the export flux of carbon is usually highly seasonal and often episodic, a short-term measurement produces data that is only useful for limited special purposes. It is therefore critical to collect sediment in time series for at least a year. Though this is not as technologically easy as this simple description may sound, the time-series sediment trap array method, together with multidisciplinary ocean measurements, has recently brought large leaps in the understanding of basinwide dynamics of the biological pump in relation to such global oceanographic phenomena as El Niño and the Asian monsoons. Sediment trap experiments have come to be one of the principal methods for understanding global CO_2 cycles in the ocean.

We now have 15 years of time-series, sediment-

Integration of sediment trap based measurements from a variety of locations allows investigators to estimate the global flux of carbon to the ocean's interior.

Organic Carbon Export Fluxes



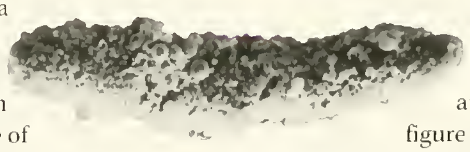


Jack Cook (and thanks to Dan McCorkle)

trap data collected from the interior of the world's open oceans through the collaborative effort of an international group of scientists, including the WHOI PARFLUX group. We are finally beginning to understand the pattern of basin-to-basin export-flux variability and to make intelligent estimates of the flux of CO_2 carbon in particulate matter to the ocean's interior. A sediment trap collects not only carbon products but also other kinds of particles: For example, we have found that the export flux of biogenic silica produced by plankton with siliceous frustules and tests provides important information for understanding another type of basin-scale biological pump (see Arabian Sea article on page 24).

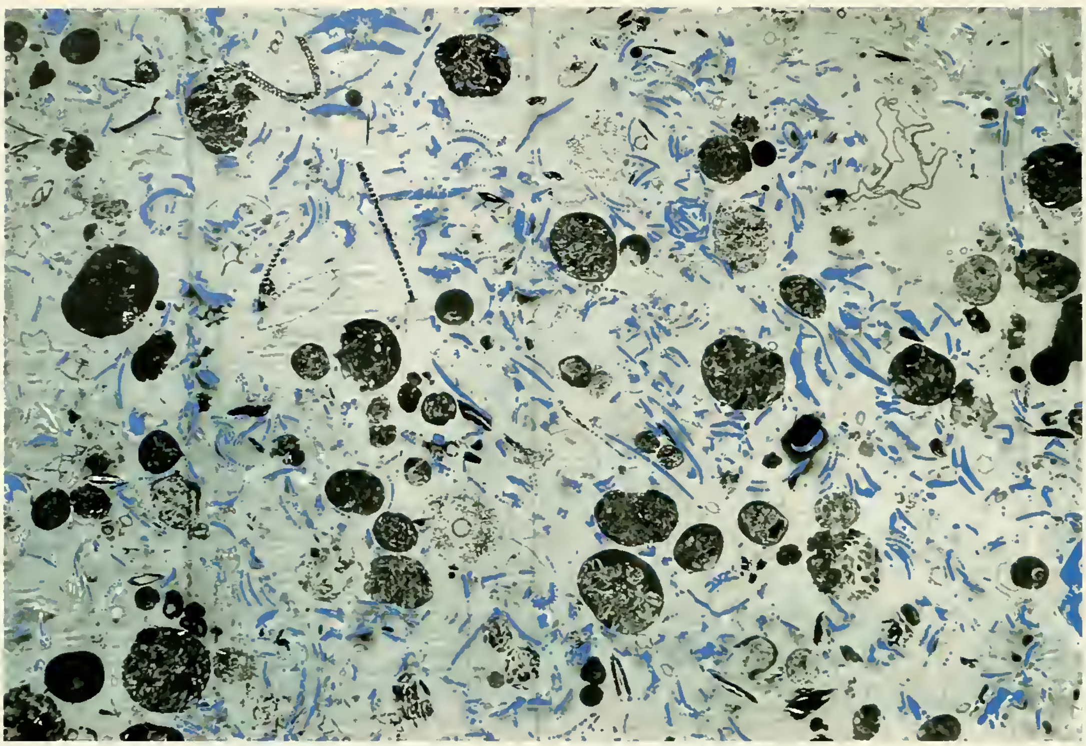
By integrating sediment trap based measurements (figure opposite), we estimate the global flux of carbon to the ocean's interior at 0.8 gigaton, nearly one billion tons, per year—0.35 gigaton in organic carbon and 0.44 gigaton in inorganic carbon (calcium carbonate). The global calcium in carbonate and silicon in biogenic opal export fluxes are 2.9 and 1.4 gigatons per year, respectively. Interannual fluctuation of global export production is unknown, as we are far from understanding the interannual changes in overall primary production.

Our 15-year export flux data set reveals distinct "biogeochemical regions" where the biological pump operates in two significantly different modes known as "Carbonate Ocean" and "Silica (Opal) Ocean" (see figure above). A Carbonate Ocean is defined as the condition in which sinking particles deliver more carbonate than silica to the ocean interior, as well as more inorganic than organic carbon. In a Silica Ocean, these ratios are reversed. To date, these conditions are only observational, and we are anxious to determine the reasons for



Conditions that influence removal of carbon-dioxide carbon from atmosphere to deep ocean are illustrated here and discussed in the article.

Fecal pellets are about the size of a comma (,).



Susumu Honjo

Transmision electron microscope image (enlarged some 3,000 times) of a section of a fecal pellet collected by a sediment trap in the North Atlantic. It includes undigested, phytoplankton cell organelles, including chloroplasts. The blue (artificially colored) areas represent remains of coccoliths that were eaten by a zoolankter and passed unaffected through the gut. Coccoliths are composed of nearly pure calcite, the heaviest mineral produced by marine organisms, which makes a fecal pellet heavy enough to settle rapidly through the water column.

this partition in the ocean. Global distribution of dissolved silica and other essential nutrients, which is controlled by very large scale ocean circulation, might be the deciding factor in this partition. The majority of present seas are Carbonate Oceans while Silica Oceans account for less than 20 percent of the world ocean. The export flux of organic carbon in a Silica Ocean is usually higher than that in a Carbonate Ocean because their biological pumps function differently: Photosynthesis of diatoms, whose shells are largely composed of silica, is the mechanism for primary production in a Silica Ocean, and photosynthesis of coccolithophorids, whose shells are largely composed of calcium carbonate, is the primary producer in a Carbonate Ocean.

At present, one of the most typical Silica Oceans is the sub-Arctic Pacific north of 45°N, an area that includes the Bering Sea, the Sea of Okhotsk, and the northern East Sea (Japan Sea). By contrast, most of the North Atlantic is a Carbonate Ocean. Nutrient availability is the major oceanographic difference between these seas. Layers rich with dissolved nutrients underlie the sub-Arctic Pacific at about 600 meters: at 2,000 meters the dissolved silica maximum is reached. In contrast, the amount of silica in the northern North Atlantic is an order of magnitude less than in the sub-Arctic Pacific.

In the northern North Atlantic, upper ocean waters sink due to thermal exchange and are replaced with nutrient-depleted surface waters supplied from the south. This results in a negative silica mass balance in the upper layers in this area and allows coccolithophorids to take over the niche from the diatoms because coccolithophorids need no dissolved silica to grow. On the other hand, the upper layers of the sub-Arctic Pacific are enriched by the upwelling of dissolved silica. A large flux of biogenic opal particles is supplied to the relatively shallow but vast shelves and slopes in the Sea of Okhotsk and the Bering Sea and is recycled to the upper waters, generating the positive feedback loop of a "silica trap." Thus the ecosystem is essentially occupied by diatoms, and relatively scarce coccolithophorids appear only when the surface ocean is temporarily depleted of silica at the end of the export-flux bloom.

The biological pump operating in a Silica Ocean removes CO_2 carbon from the upper to the deep ocean in the form of particulate organic carbon on a short time scale of a few to several weeks (see Arabian Sea article on page 24). The biological pump in a Carbonate Ocean also removes carbon from the atmosphere and upper oceans in the form

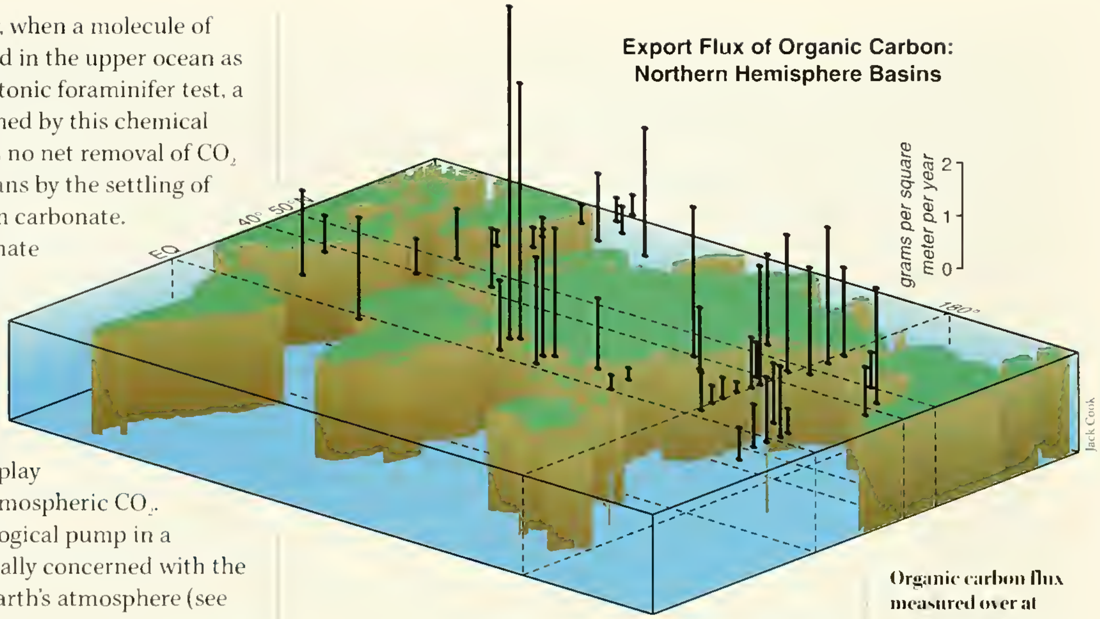
Tom Kleindinst

Author and co-editor of this issue Sus Honjo looks over some of the thousands of scanning electron micrographs taken in his laboratory for particle flux and other studies over the last 30 years.

of organic carbon. However, when a molecule of calcium carbonate is formed in the upper ocean as part of a coccolith or planktonic foraminifer test, a molecule of CO_2 is also formed by this chemical reaction. Therefore, there is no net removal of CO_2 carbon from the upper oceans by the settling of inorganic carbon as calcium carbonate. Secretion of calcium carbonate in the upper ocean by organisms reduces alkalinity, resulting in an environment less capable of absorbing atmospheric CO_2. Therefore, a Carbonate Ocean does not play a large role in removal of atmospheric CO_2. The significance of the biological pump in a Carbonate Ocean is principally concerned with the long term CO_2 balance in Earth's atmosphere (see figure on page 5).

As soon as they leave the upper ocean where they are produced, almost all of the coccoliths and foraminifera settle to the deep ocean floor within a short time. There the oxidation of organic matter that begins in the upper ocean causes an increasingly acidic condition, which results in dissolution of the coccoliths and foraminifera. Indeed, researchers find it strange to retrieve a large quantity of perfectly preserved coccoliths and foraminifera tests from a sediment trap that has been moored above a deep Pacific seafloor that consists of nothing but red clay and a few fragmented calcareous remains.

The deep ocean water, whose increased alkalinity is due to the dissolution of calcium carbonate, moves in such deep currents as the thermohaline driven circulation that runs south from the northern North Atlantic, proceeds as a bottom current through the Indian Ocean, and eventually upwells in the northern North Pacific (See *Oceanus* Vol. 39, No. 2). This mass of formerly deep water that has moved to the surface is thought to be a major absorber of atmospheric CO_2. This mechanism is often called the Alkalinity Pump (different from the Biological Pump). Note that this process is too slow to affect the CO_2 cycle of today's Earth—it takes several centuries for the ocean's deep-water circulation system to complete a turnover. Our present climate is greatly dependent on foraminifera that lived, died, and dissolved when Vikings roamed the ocean! In other words, calcium carbonate that sinks to the deep corrosive ocean is a "savings deposit" regulating future greenhouse effects of planet Earth well into the next millennium.

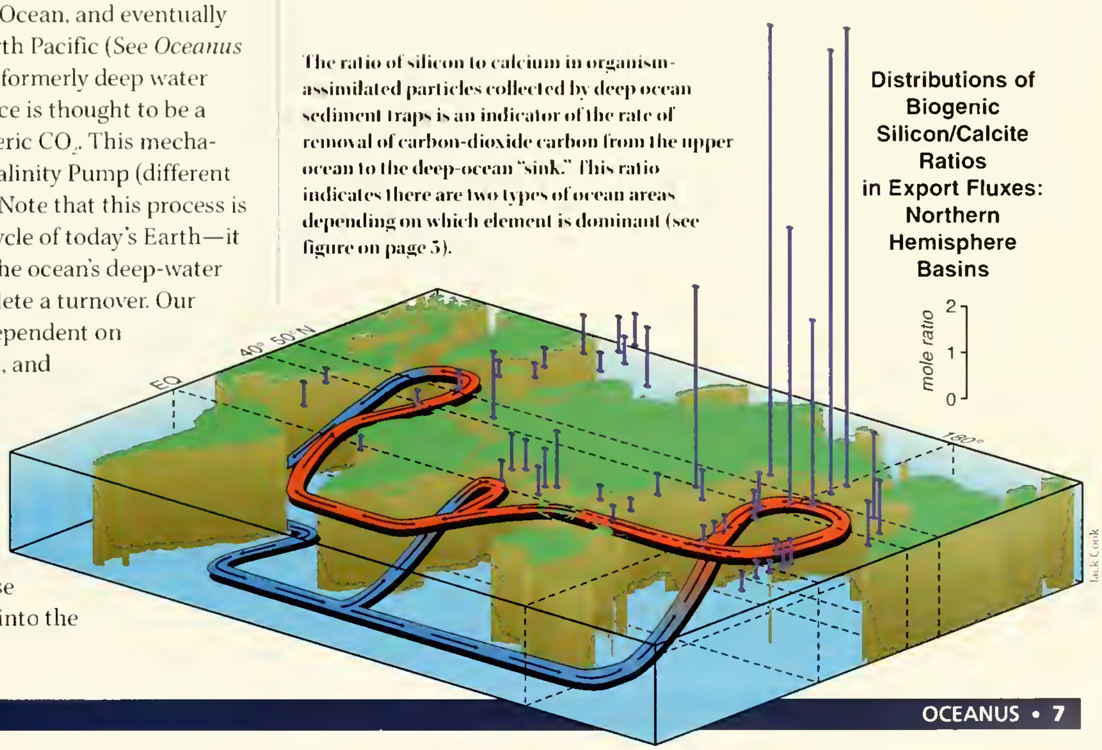


Organic carbon flux measured over at least one year with time-series sediment traps in the Northern Hemisphere in grams per square meter per year. This figure integrates data derived from sediment traps around the world, including WHOI PARFLUX results. Note the huge export flux in the Arabian Sea and relatively large annual flux in the northwestern Pacific. The "biological pump" works efficiently in these areas compared to the mid ocean.

Major funding sources for Sus Honjo's sediment trap work have been the National Science Foundation and the Office of Naval Research.

During his long research career at WHOI, Sus Honjo has concentrated on understanding the processes and rates of ocean sedimentation and the removal of carbon in the form of carbon dioxide from the atmosphere to its deep ocean "sink." He recalls trembling with excitement when he looked into a microscope aboard R/V Knorr *to examine the first sample collected by a deep ocean sediment trap in the central North Atlantic: Abundant fecal pellets produced by surface organisms proved his hypothesis that the majority of ocean sediment is delivered to the deep seafloor by large, rapidly settling aggregates. His global research efforts to link upper and deep ocean processes bridge marine geology, ocean chemistry, and biology and enhance understanding of the biogeochemistry of the ocean. As we prepared this issue, he was sending cruise reports from the southern ocean near Antarctica where he was leading a team of "trappers" and seafloor sediment research groups from WHOI and other US institutions in rough seas aboard NSF's ice breaker/research vessel* Nathaniel B. Palmer.

The ratio of silicon to calcium in organism-assimilated particles collected by deep ocean sediment traps is an indicator of the rate of removal of carbon-dioxide carbon from the upper ocean to the deep-ocean "sink." This ratio indicates there are two types of ocean areas depending on which element is dominant (see figure on page 5).



Keith Bradley

Honjo's early sediment traps were large, gray cones, often deployed in pairs.

Catching the Rain

Sediment Trap Technology

WHOI Senior Engineer Ken Doherty developed the first sediment trap in the late 1970s for what has come to be known as the WHOI PARFLUX (for "particle flux") group. Working closely with the scientific community, Doherty has continued to improve sediment traps for two decades, and these WHOI-developed instruments are widely used both nationally and internationally in the particle flux research community. Because ocean particle flux research encompasses nearly all areas of biogeochemistry, the trapped samples are shared by many programs to take advantage of interdisciplinary cooperative research. This is one reason why the trap opening must be relatively large, to collect enough samples to share with many programs. Many time-series sediment traps have openings at least half a meter square, which results in an instrument about one meter in diameter—time-series traps may be the largest instruments routinely deployed along moorings. However, we do expect that improved analytical methods will allow future reduction in the size of time-series traps used for multidisciplinary research.

Sediment traps require great mechanical strength, as they are often deployed for as long as a year or more, and then redeployed immediately after recovery of samples. Titanium is used extensively where strength is a critical requirement, such as in the structural frame and in the chamber that houses electronics under great pressure. Titanium is light yet as strong as steel and has virtually no reaction to seawater. Various industrial plastics that are very stable in the deep ocean are also used. The opening and closing of a trap requires a reliable mechanism

Courtesy Susumu Honjo

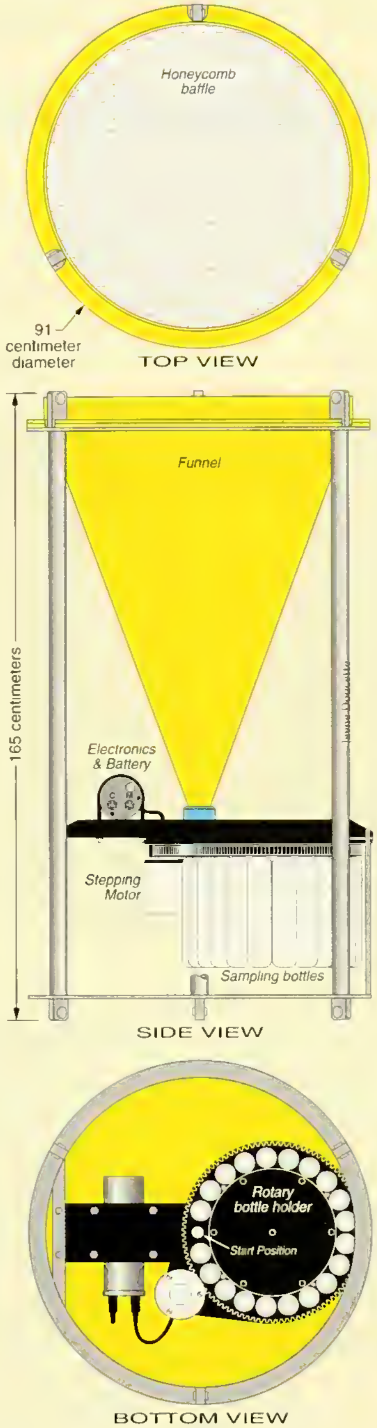
These smaller, yellow cones show the current design. Research Specialist Steve Manganini, who has been involved in some 32 sediment trap deployments in several oceans, is at center.

with many moving parts. The shorter the open period, the better the temporal resolution. However, a shorter collection period requires more collection cups, and there is a limit to the number of cups a trap can accommodate. For a given trap diameter, a short open duration catches less volume of sample. Balancing the need for high temporal resolution with the engineering limitations, many scientists have set a unit duration of about two weeks, and cover a year with some 20 open periods. Sampling cups are opened sequentially: As one cup completes its open period, it rotates away from the base of the funnel opening and a new cup moves to the position, allowing no break in the collection of raining particles. Other than the one that is open, cups are sealed from the ambient water until recovery. In an effort to find a method to keep organic-matter samples in the trap in the best possible condition until they can be retrieved, scientists have tested many preservatives, and a formalin solution is now considered best for general purposes.

Through control technology, Doherty's design allows a scientist to program the entire open/close schedule into a trap's microcomputer from a laboratory PC before deployment. This enables the scientist to use, for example, periods of exactly equal duration throughout the experiment, to open/close frequently during an expected bloom season, or to sample for longer periods in winter when the ocean is less active. Another option might be to open and close in response to signals from various sensors such as turbidity, currents, etc.

There are still questions, however, about whether a trap (of any design) collects all of the particles settling through the water column. Experimental and modeling research on the behavior of settling particles is in progress, and the questions are also being addressed by an ingenious method using isotopes that are absorbed by particles that remain in the water column (see article on page 29).

The sediment trap must be kept stable, maintaining its upright position at all times during its deployment, and



The sampling bottles rotate on a schedule programmed before the instrument is deployed, each collecting about 5 days' to a month's worth of "rain" before being sealed for analysis upon recovery of the sediment trap. At right is a diagram of an Arabian Sea mooring that included PARFLUX traps (yellow cones) for WHOI–Oregon State University joint research and traps specially designed for biochemical studies (red squares) by researchers from the State University of New York–Stony Brook, Skidaway Institute of Oceanography, and the University of Washington.

it must also be retrieved intact. WHOI Research Specialist Steve Manganini, with the cooperation of other Institution buoy engineers, has made continuous improvements to the deep water sediment trap mooring system. Since 1979, Steve's team has achieved 100 percent recovery of PARFLUX sediment traps. They study computer models of mooring behavior and buoyancy and then adjust mooring component designs to reduce the tilting and lateral motion of traps located along the taut line. The mooring line is usually composed of galvanized steel wire jacketed with plastic sheathing. A time-series sediment trap mooring is made up of hundreds of parts, including a large quantity of line, wire rope, and other hardware that are all carefully loaded onto the research vessel.

A deep-ocean time-series mooring is typically set, say, 3 to 5 kilometers deep. In order to avoid collecting particles resuspended by boundary conditions just above the seafloor, the deepest trap is generally deployed about 0.5 kilometers above the bottom. Traps are also often deployed at depths of 1 kilometer and 2 kilometers. Our PARFLUX group pioneered synchronization of the open/close timing of multiple traps to trace particles in time and space. We have extended this from a single mooring to synchronization of many moorings.

Areas where cross-basin arrays have been deployed by JGOFS (the Joint Global Ocean Flux Study) and other programs include several locations in the Pacific and Atlantic Oceans, the Arabian Sea, the East (Japan) Sea, and the southern ocean around Antarctica. These arrays enable scientists to study the multidimensional processing of particles in a large oceanic basin over long periods of time. Currently, an international group of scientists is synchronizing traps that are or will be deployed in the Arabian Sea, Sea of Bengal, South China Sea, East/Japan Sea, and the northwestern Pacific. This giant time-space network will provide important information on how Asian monsoons affect biological pump removal of carbon dioxide carbon from the atmosphere to the ocean's interior.

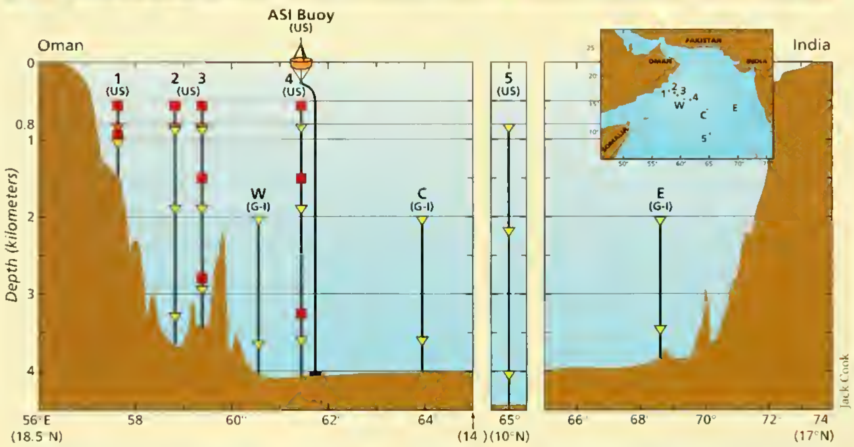
—Sus Honjo

Deploying the Rain Catchers

Deployment of a deep-ocean sediment trap mooring begins with the ship heading slowly into the wind. The mooring line, with the various instruments attached in top-to-bottom order, is paid out over the stern from a winch and pulled away from the ship, straight behind, seemingly almost on its own power. First over the stern is the top of the mooring, whose radio beacon and flashing light are designed to operate only when they are on the surface. Next comes a cluster of 20 floats, each capable of supporting 50 to 60 pounds in water, to provide upper-mooring buoyancy. These floats are all made of thick, plastic-covered glass spheres designed to withstand the great pressure of the deep ocean.

Next on the mooring line comes the shallowest sediment trap. Additional instruments such as a current meter are often deployed with the trap. This float/trap sequence is repeated until the end of the mooring line is reached and all the instruments are laid out along the surface. An acoustic release is connected near the end of the mooring. This critical device will be commanded to release the mooring from the anchor, allowing it to return to the surface at the end of the collection period.

Lastly, an anchor, usually about a ton of used freight car wheels, is connected to the lower end of the release with a long, highly flexible nylon line that stretches to absorb the landing impact. While a team of technicians and deck personnel are engaged in the laying out process, the bridge maneuvers the ship to the designated mooring location, passing a certain distance beyond where the anchor is to be set. When ready, the anchor is dropped into the ocean with a sizable splash. As the anchor sinks, the mooring line is pulled into the water, and one by one the traps and other equipment disappear from the surface. Finally, the radio signal goes silent as it slips beneath the waves. Resistance from the mooring pulls the anchor back a certain distance that we have allowed for from our modeling. The moment the anchor arrives on the ocean floor, its precise location can be calculated through acoustic communication from the ship to the release.



Working aboard R/V *Thomas Thompson* (University of Washington). Steve Manganini (black shirt) manages the launch of one of the sediment trap moorings shown in the illustration. The array extended over 1,850 kilometers between Oman and India with the various traps synchronized to open and close simultaneously.

When the deployment period is over, usually a year, a ship will again be exactly positioned over the mooring, using satellite navigation. Technicians "talk" with the acoustic release near the anchor with a transducer—a microphone for communicating through the water column—and tell it to free the mooring from the anchor. In a short time, the bright orange floats at the summit of the mooring appear on the surface and the radio beeps. The rest of the recovery protocol reverses the deployment procedure. Traps and floats are picked up one by one and the mooring wire is wound on the winch. Finally, the acoustic release is recovered and the mooring crew can take a break—until it's time to redeploy the moorings.

—Sus Honjo

Ground-Truthing the Paleoclimate Record

Sediment Trap Observations Aid Paleoceanographers

William B. Curry
Chairman, Geology and Geophysics Department
Dorinda R. Ostermann
Research Associate, Geology and Geophysics Department

The geological record contains a wealth of information about Earth's past environmental conditions. During its long geological history the planet has experienced changes in climate that are much larger than those recorded during human history; these environmental conditions range from periods when large ice sheets covered much of the northern hemisphere, as recently as 20,000 years ago, to past atmospheric concentrations of greenhouse gases that warmed Earth's polar regions enough to melt all of the ice caps 50 million years ago. Since human civilization has developed during a fairly short period of unusually mild and stable climate, humans have yet to experience the full range of variability that the planet's natural systems impose. Thus, the geological record has become an extremely important archive for understanding the range of natural variability in climate, the processes that cause climate change on decadal and longer time scales, and the background variability from which greenhouse warming must be detected.

One of the principal archives of climate information is the fossil record in deep sea sediments. For many years it has been known that seawater temperature plays an important role in the biogeography of many organisms living in the oceans: Tropical and polar regions foster different species. Using the fossilized remains of these organisms in deep sea sediment cores, marine geologists can reconstruct past changes in sea surface temperature and produce records that document past variations in sea surface conditions caused by changes in the earth-sun orbital geometry and by abrupt changes in ocean circulation. The major fossil-producing organisms for this type of research have been the foraminifera, single-celled animals with planktonic (floating) and benthonic (bottom-dwelling) varieties. These organisms produce an easily identified sand-grain-sized structure made of calcium carbonate (called a test) that is unique for each species and is well preserved in sediments

Research Associate Dorinda Osterman removes sample cups from a sediment trap recovered aboard the Icelandic Research Vessel *Bjarni Sæmundsson*.

found in nearly all of the major ocean basins.

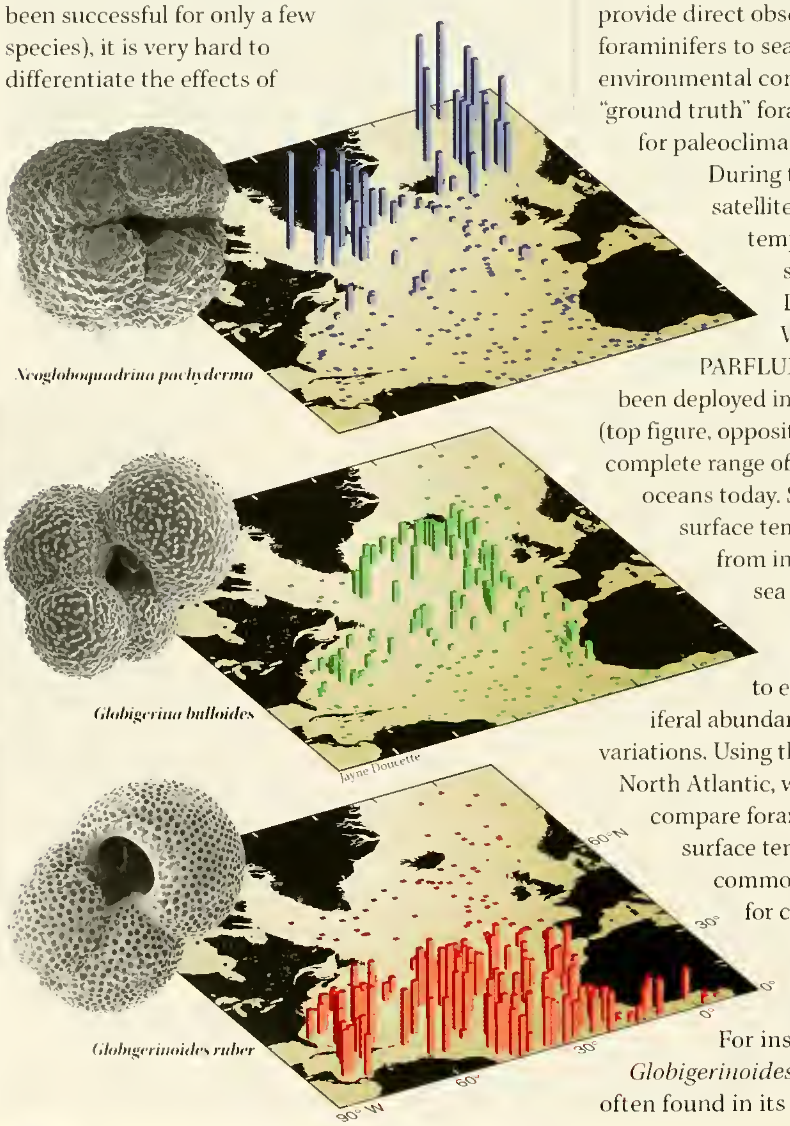
Early 1980s studies of the geographic occurrence of the various species of foraminifera suggested that temperature was a primary control on their distribution. The observations were based on plankton tows of the upper water column and the distribution of fossilized remains in surface sediments of the seafloor below. The species could easily be grouped into tropical, subtropical, and polar assemblages (see figure below), and the parallels with the sea surface temperature distribution were obvious. By mapping the distributions of these species, estimates of past sea surface temperatures were made and paleoceanography was born.

The accuracy of these reconstructions, however, is difficult to assess because biological systems are affected by many more environmental variables than temperature alone and because many of the environmental factors co-vary. For instance, salinity and temperature are highly correlated in the oceans because warmer waters are more likely to have experienced the evaporation that causes greater salinity. Without culturing these organisms in the laboratory (a difficult procedure that has been successful for only a few species), it is very hard to differentiate the effects of salinity changes from temperature changes. We are left with finding alternative ways to document their usefulness as temperature indicators. Using modern observational systems, including sediment traps and satellites, we are evaluating the reliability of foraminifera for temperature estimates under realistic conditions in today's oceans.

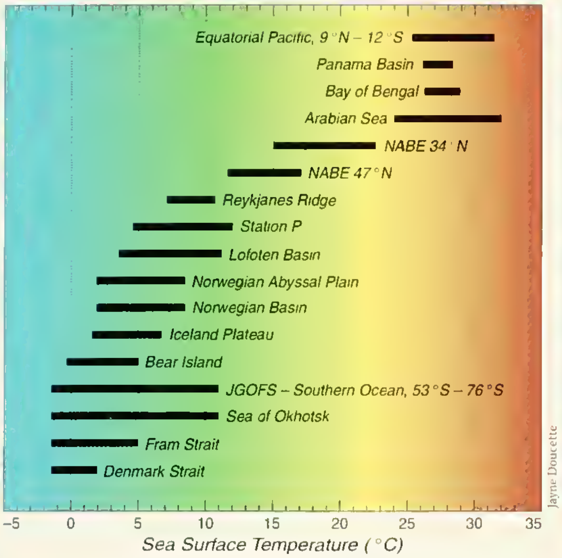
Sediment traps are suspended on moorings to sample debris settling through the water column, debris that includes the fossil remains of planktonic foraminifera. Since sediment traps can collect time series samples with preprogrammed temporal resolutions of several weeks to several months, foraminifers, with several-week life spans, are ideally suited for collection using these moored instruments. Indeed, sediment trap samples often contain foraminiferal abundances implying a "rainfall" of several hundred to several thousand individual tests per square meter per day. Joint Global Ocean Flux (JGOFS) program studies of the North Atlantic spring plankton bloom, upwelling in the equatorial Pacific Ocean, the monsoon system in the Arabian Sea of the Indian Ocean, and the processes of the southern ocean around Antarctica provide direct observations of the sensitivity of foraminifers to sea surface temperature (and other environmental conditions). They allow us to "ground truth" foraminiferal abundance variations for paleoclimate reconstructions.

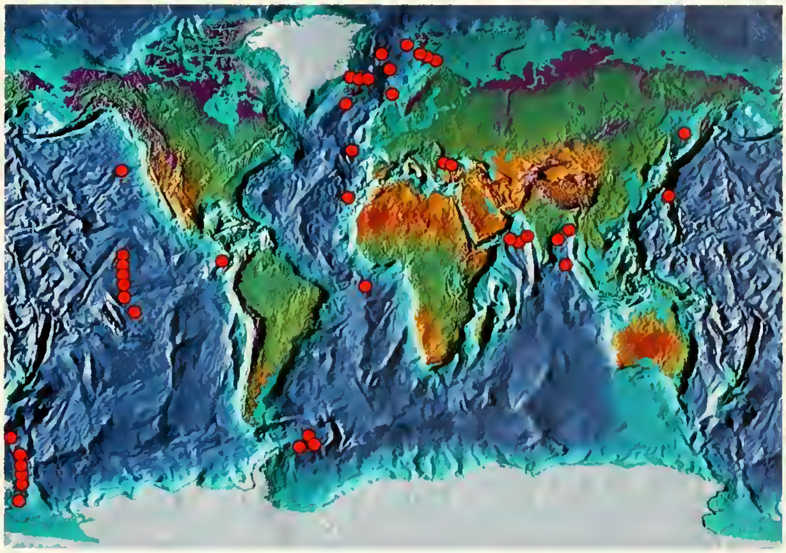
During the last decade we merged satellite observations of sea surface temperature with a global data set of sediment traps deployed by the PARFLUX research group at WHOI led by Susumu Honjo. PARFLUX sediment trap systems have been deployed in all of the major oceans basins (top figure, opposite page) and have sampled the complete range of temperature observed in the oceans today. Satellite observations of sea surface temperature, which are calculated from infrared radiation emitted from the sea surface, provide "real-time" information on changes in surface water temperatures and allow us to evaluate the changes in foraminiferal abundance in terms of temperature variations. Using the subset of samples from the North Atlantic, we have been able to directly compare foraminiferal abundances and sea surface temperatures for three of the most common and useful foraminiferal species for climate reconstructions.

The relationships between foraminiferal abundances and temperature can be dramatic. For instance, the tropical species *Globigerinoides ruber* (named for the pink color often found in its test) is not found in sediment



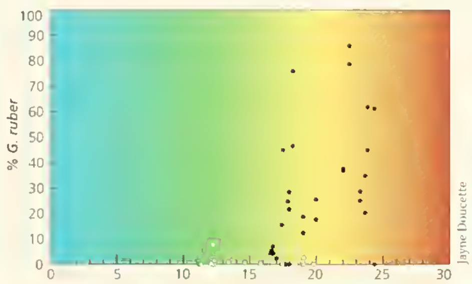
Distribution maps and scanning electron microscope images for three foraminifers. The height of each bar indicates the relative abundance of the species as a percent of the total foraminifer assemblege. *N. pachyderma* (left coiling) in the top figure prefers water colder than 8 degrees centigrade. *G. bulloides* in the middle figure prefers waters that are influenced by the Gulf Stream. *G. ruber* in the bottom figure prefers warm central North Atlantic water.



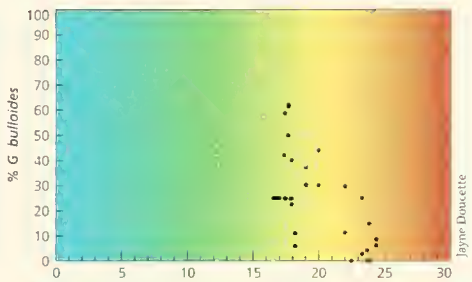


trap samples when surface temperatures fall below 16°C. When the surface water warms to 23°C, the species abundances (expressed as the percentage of the organism in the sample) increase to a maximum of about 80 percent of the assemblage. In the PARFLUX North Atlantic data set, the surface water temperatures never exceeded 24°C, so we are not sure of this species' temperature relationship in warmer waters. For paleoceanographic usefulness, finding this species in a sample from a sediment core can immediately determine that surface waters were warmer than 16°C; finding it in very high abundances implies that the surface waters were much warmer. Using its abundance variations in the past, we can place constraints on the surface water temperatures above the sediment core at the time the sediment was deposited. When the sediment deposits are placed within a chronology using radiocarbon dating, we can reconstruct the past variations in temperature, observe their relationships to changes in ocean and atmospheric chemistry, and determine the rate and range of natural variations in the climate system.

In the modern ocean there are more than 30 species of planktonic foraminifera, each with its own tolerance range of temperature and other environmental variables. By using the species together it is possible to constrain temperatures over the full range of conditions observed in the oceans today. For colder water species the relationships with temperature are just as striking and also have proven extremely useful. The highest abundance of *Globigerina bulloides*, for instance, is generally found in the mid range of surface water temperatures, from about 10 to 25°C, with highest abundances at about 17°C. This species is also found in very high abundance in regions with very high productivity caused by coastal upwelling, which complicates its relationship to temperature. For instance, *G. bulloides* is in high abundance in Arabian Sea waters as warm as 24°C.



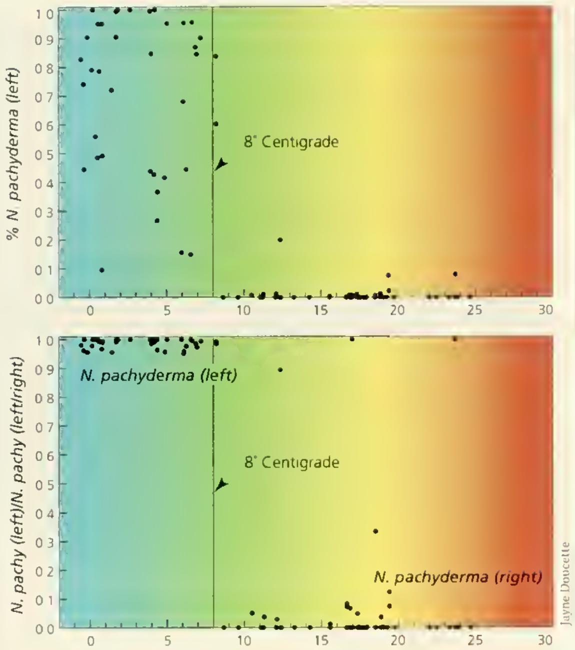
Distribution of G. ruber (percent of total foraminifer population) based upon temperature of surface water obtained by Satellite data. The open circles are from the JGOFS 47°N sediment trap; closed circles are from the JGOFS 34° Nsediment trap.



Distribution of G. bulloides (percent of total foraminifer population) based upon temperature of surface water obtained by satellite data. The open circles are from the JGOFS 47°N sediment trap; closed circles are from the JGOFS 34°N sediment trap.

The polar bear of planktonic foraminifera, *Neogloboquadrina pachyderma*, is found only in polar regions and comes in two forms, differentiated by its coiling direction. The left-coiling variety, which runs counterclockwise when viewed on its aperture, is found in greatest abundance in the coldest waters of the North Atlantic and is nearly absent from regions where surface waters are warmer than 8°C. The right-coiling variety is almost never present in the colder waters, but dominates the *N. pachyderma* population in warmer waters. Thus this coiling direction and abundance change at 8°C makes the species especially useful for tracing the past position of the 8°C isotherm. The location of this isotherm is closely related to the extent of deep water convection

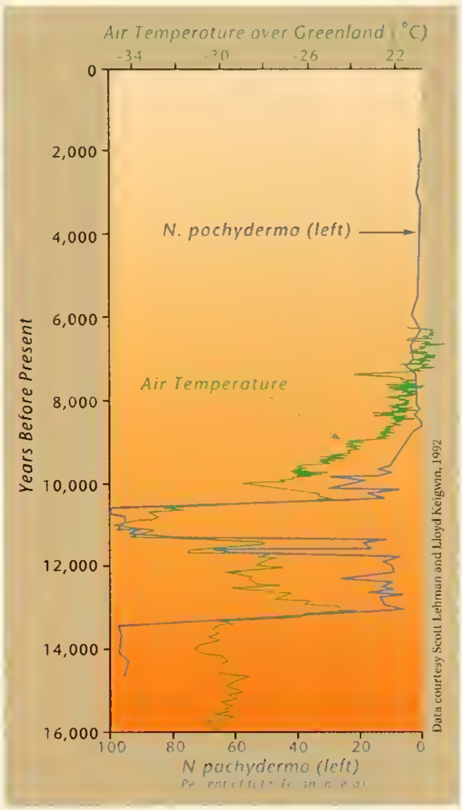
All biogenic particles arriving on the ocean floor carry a memory imprint of their growth environment. Fossil shells of foraminifera contain many clues to the past oceanic environment, including temperature and salinity information. The chart above left shows the range of sea surface temperatures sampled by WHOI time-series sediment traps around the world from less than -2°C to greater than 32°C. The world map indicates the locations of these sediment traps.



The top panel shows distribution of *Neogloboquadrina pachyderma* (left coiling) as a percent of total foraminifer population based on surface water temperature obtained from satellite data. Abundances of this species increase in water below 8°C. The lower panel shows an abrupt change in *N. pachyderma* coiling direction from left to right when the surface water warms above 8°C.

occurring in the North Atlantic (see Oceans and Climate issue of *Oceanus*, Vol. 39, No. 2).

Past variations in the abundance of *N. pachyderma* have documented that ocean circulation is closely linked to the rapid changes in climate observed throughout much of the last glacial interval on earth and that many of these rapid oscillations in climate occur on time scales as short as several decades. Oscillations in *N. pachyderma* abundance document large geographic swings in the position of the sea surface temperature fronts in the North Atlantic Ocean, swings that are apparently synchronous with large, rapid changes in air temperature (fluctuations of more than 12°C in several decades) as recorded by changes in the chemistry of ice in cores extracted from the Greenland ice sheet. These fluctuations in *N. pachyderma* abundance document the incursions of warm salty waters into the high latitude regions where deep water production occurs. Cooling of this salty water increases its density, causing it to sink and form deep water that flows southward at depth. This process releases heat from the surface water, causing the North Atlantic region to warm by nearly 5°C.



Air temperature over Greenland (based on ice core isotopic measurements) and sea surface variability in the North Atlantic (based on left-coiling *N. pachyderma* percentages). The covariation of the records implies that variations in the circulation of the North Atlantic are strongly linked to temperatures in the region.

Jayne Doucette

The extent to which we understand the link between climate change and ocean circulation depends to a great extent on these geological records because measurements of atmospheric conditions and oceanic convection are reliable for only about the last 50 years. Though there are clearly identifiable links emerging from the atmospheric and oceanic records for this recent period, the magnitude of the changes are small compared to the large amplitude oscillations seen in the geological record. Likewise, future monitoring of changes in ocean convection and climate may also be small and will take place on time scales of 10 years or longer, thus making it difficult to identify the causes of the changes. Adding the larger, more dramatic changes seen in the geological record to the history of ocean circulation will help to constrain the factors that cause alterations in ocean circulation and increase our chances for improved prediction of future climate. But our geological reconstructions will only be a good as our understanding of the ecological factors governing today's biota.

This research was supported by the National Science Foundation and the Office of Naval Research. In addition, the authors are indebted to the government of Iceland and the Marine Research Institute in Reykjavik for their help in maintaining several sediment trap mooring stations near Iceland. Particular thanks goes to Jón Ólafsson for his continued support and collaboration.

Bill Curry and Rindy Ostermann first met in February of 1980 on the Caribbean Island of Roatan. Bill was joining the crew of Sea Education Association's sailing vessel Westward *for a two week stint as visiting scientist. Rindy had been on board for four months as a staff scientist and notes that Bill's midwinter Cape Cod complexion was quite striking next to the tans of the seasoned crew aboard* Westward. *Bill hoisted himself over the rail and headed for Rindy at the bow where he delivered a hug and a kiss from mutual friends in Woods Hole. Thus began a working relationship between the two that continues to this day. Bill is currently in the middle of a four-year term as Geology & Geophysics Department Chair. Rindy runs Bill's lab and the Micropaleontology Mass Spectrometer for a group of five scientists. She calculates that she has spent more than five years of her life at sea collecting the samples discussed in this article.*

October 1997: Deployment of the Oceanic Flux Program sediment trap mooring aboard R/V *Weatherbird II* (Bermuda Biological Station). Sinking material will be collected in the sample bottles on the rotating plate affixed to the bottom of the trap funnel. The large yellow balls are "hardhats" housing glass deep sea floats.

The Oceanic Flux Program

Twenty Years of Particle Flux Measurements in the Deep Sargasso Sea

Maureen Conte
Associate Scientist, Marine Chemistry & Geochemistry Department

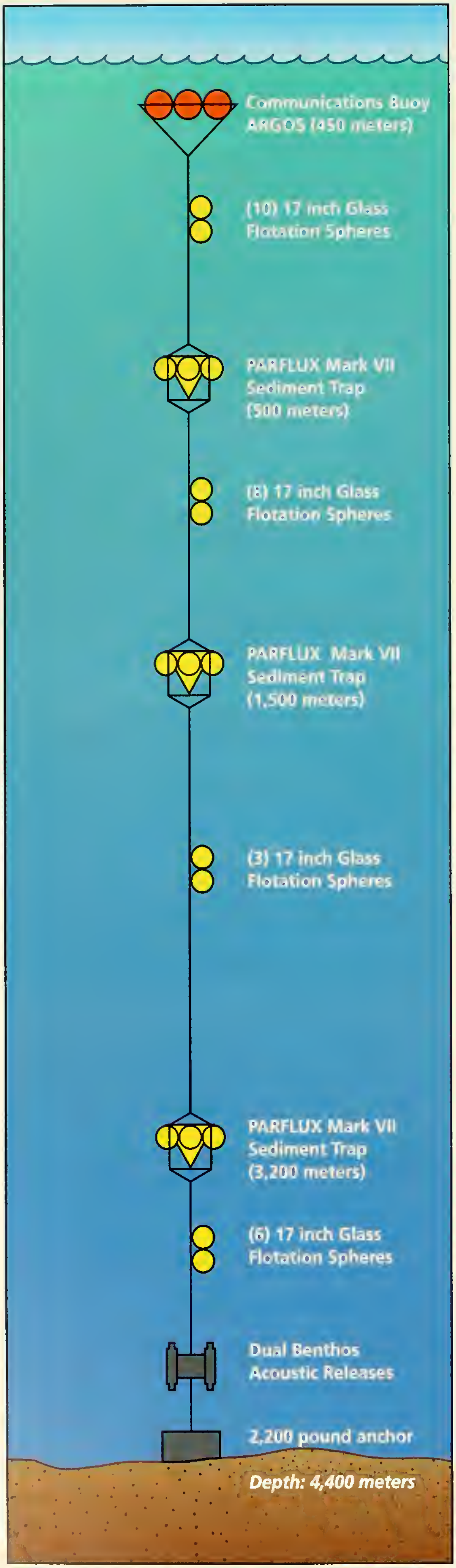
October 14, 1997: The predawn hours at sea have a unique feel—an eerie stillness, regardless of weather. This morning is no exception as the Bermuda Biological Station's R/V *Weatherbird II* approaches the OFP (Oceanic Flux Program) sediment trap mooring some 75 kilometers southeast of Bermuda.

May 1977: Werner Deuser's first sediment trap is ready for its initial entry into the sea. The ship's crane was used to lower this large trap into the water.

The top of the mooring is subsurface, so we rely on the ship's GPS (Global Positioning System) navigation to locate the exact mooring position. There's a small ground swell, a freshening breeze, and a sliver of yellow moon setting as we lower the acoustic transducer over the starboard beam. After presetting the deck unit with appropriate frequencies, I send interrogation signals to one of two releases near the bottom of the mooring—a distance of four thousand meters below the sea surface. The deck box light flashes, indicating receipt of the release's acoustic response, and the range is displayed on the readout. Thanks to GPS, we are directly over the mooring.

I communicate with the releases a few more times to confirm distance and then switch frequencies to command one of the releases to retract a pin that holds it fast to the anchor line. A double flash on the deckbox indicates an affirmative response from the signaled release, and the mooring, free of its anchor, begins to ascend. When it reaches the surface, the communications buoy transmits a radio signal and its strobe begins to flash. We head to the bridge deck where we earnestly scan the horizon for

The Oceanic Flux Program (OFP) sediment trap mooring is four kilometers long and consists of three sediment traps, deep sea floats, dual acoustic releases and a communications buoy. The buoyancy along the mooring string is carefully engineered to keep the mooring vertical and to ensure that it comes up tangle free when recovered.



Jack Cook

the strobe and listen for the radio signal.

On target—success! Strobe off the port bow! Sediment traps bobbing in the swell! With smiles of relieved anxiety, we mark position and wait for full daylight to commence the 98th recovery of the OFP sediment trap mooring.

Over 20 years earlier, WHOI geochemist Werner Deuser first deployed his deep ocean sediment trap in this area near the site of the longstanding Hydrostation S time series (see *Oceanus* Vol. 39, No. 2 for an article on Station S). Advances in deep ocean mooring technology had just made it possible for Deuser and others to directly sample the rain of particles falling in the abyssal ocean by using large conical or cylindrically shaped sediment "trap" collectors. Deuser's first sediment trap was a monstrous instrument having a 1.5 square meter cross section at the funnel aperture and a single sample collection bottle at the base. After two months of sampling, the mooring was retrieved and the trap redeployed with a fresh collection bottle. A combination of rough open ocean waters and a research vessel measuring merely 65 feet (Bermuda Biological Station's R/V *Panulirus II*) made sample collection particularly arduous. But Deuser, with assistance from the Bermuda Biological Station, persisted with this grueling mooring turnaround schedule for many years. His efforts produced the first continuous time series of particle flux in the deep ocean.

By the early 1980s, Deuser surprised the oceanographic community with the observation that the amount of material sinking through the deep ocean was not constant but varied seasonally with the cycle of phytoplankton production in the overlying surface waters. This discovery directly contradicted the widely held belief that the deep ocean was a highly stable, unchanging environment. In fact, the particle flux record revealed that the deep ocean environment was quite variable and tightly coupled to upper ocean processes via a rapid delivery of particles from the surface within a time span of just a few weeks. And not only did the deep ocean flux of biogenic materials—skeletal parts of microscopic plants and animals, fecal pellets, and amorphous organic matter—vary seasonally. Nonbiological materials such as dust also varied in concert with the biogenic flux, despite differences in the timing of the dust deposition at the sea surface. It appeared that animal grazers in the surface ocean were extremely efficient at scavenging dust and other suspended particles from the water column and "repackaging" this material into larger particles that sank more rapidly. This enhancement of particle flux by biological scavenging activities is now known to be essential in the geochemical cycling of carbon and associated elements in the ocean and has been loosely termed the "biological pump."

The OFP time series, like the world around us, has undergone a few changes since 1977. The large, crude, original sediment trap has been replaced by smaller, microprocessor-controlled traps capable of collecting a sequential set of samples at accurately timed intervals in a single deployment. To address questions pertaining to the downward flux of material, we have added to the mooring new traps at 500 and 1,500 meter depths. New technologies such as GPS navigation, ARGOS satellite tracking systems, and improved acoustic releases have greatly simplified and reduced the risks associated with deploying and retrieving deep ocean moorings. Advances in laboratory instrumentation now allow detailed chemical analyses that were unimaginable when the program began and that require only minute quantities of recovered material. There have also been changes in personnel and new directions: In 1996 Deuser retired and passed the leadership of the program to me. Yet, throughout the changes of the last 20 years, an OFP sediment trap has continuously sampled the deep particle flux at this site in the Sargasso Sea.

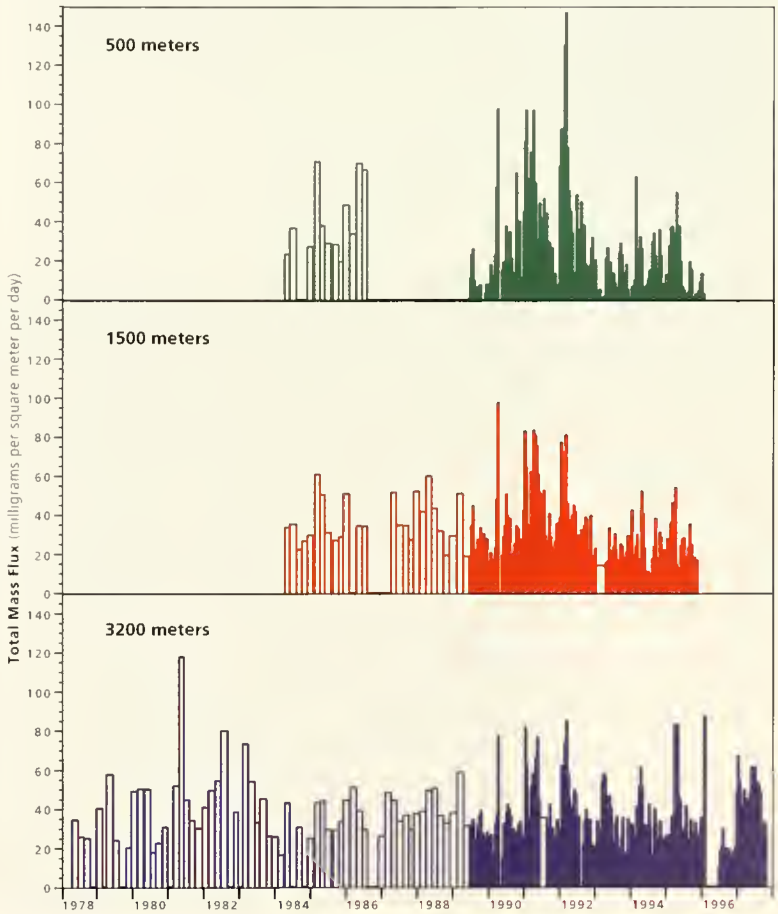
Vicky Cullen

Werner Deuser is shown here aboard R/V *Atlantis II* in 1977, the year that he initiated the first continuous time series of particle flux measurements in the deep ocean.

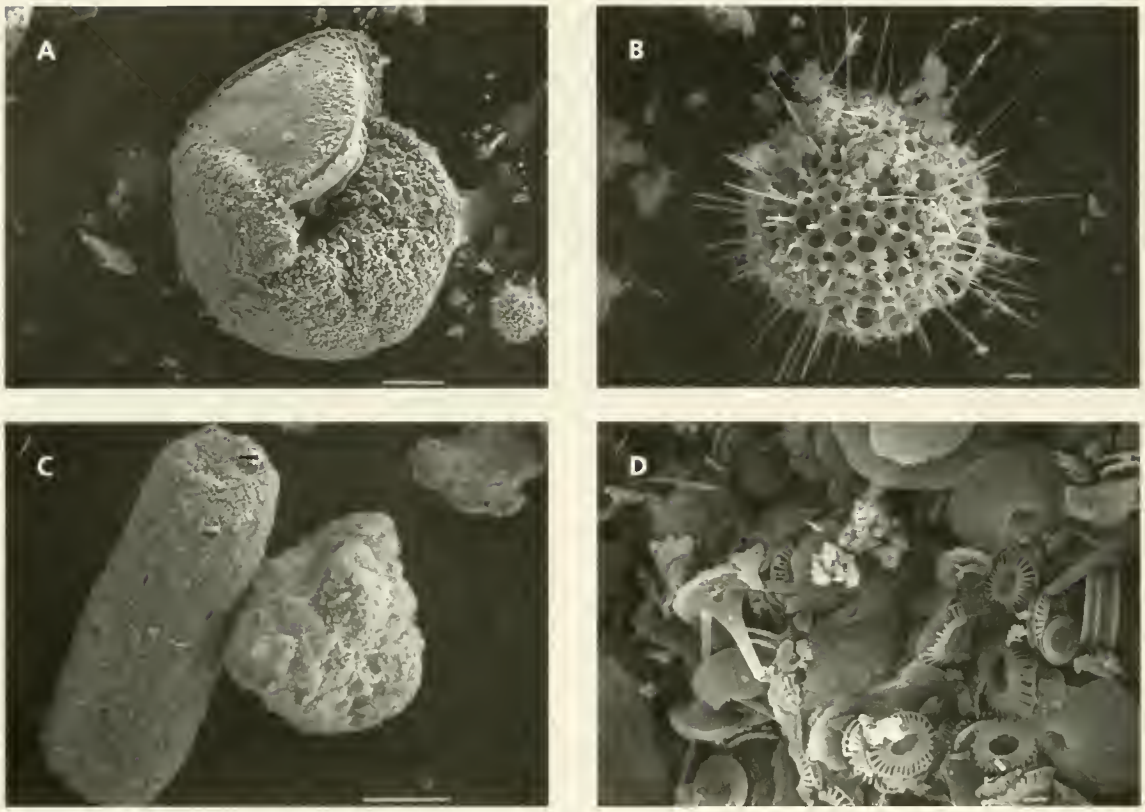
The particles landing in a deep sediment trap may have originated at the surface over a hundred kilometers away. Statistically, the catchment area of the OFP 3,200 meter trap is representative of thousands of square kilometers of surface ocean. Deep sediment traps provide a spatially and temporally integrated picture of ocean functioning that cannot easily be assessed by other types of samplers, such as water bottles, because these measure only a "snapshot" in space and time. The OFP record shows that particle flux in the deep Sargasso Sea has varied on a number of time scales, from short-lived, episodic, high-flux "events" lasting only days to a few weeks to interannual and longer term trends spanning more than a decade.

The time series, particularly the biweekly resolved flux record collected since 1989, shows marked year to year variability in the magnitude and timing of the seasonal flux maximum that is associated with the annual spring peak in phytoplankton production. Our research aims not only to measure variability in flux, which has significant implications for the biogeochemical cycling of carbon and associated elements, but also to understand the underlying causes of this variability and the relationship to upper ocean processes. This goal has been greatly assisted in recent years by the addition of other research programs in the overlying waters near the OFP site, including the US-Joint Global Ocean Flux Study Bermuda Atlantic Time-Series program of upper ocean biogeochemistry and physics, and the Bermuda Testbed Mooring, which contains a suite of novel and sophisticated instruments continuously measuring physical, chemical, and bio-optical properties of the upper water column. These programs, coupled with the deep ocean measurements, are helping to illuminate the complex dynamics linking upper ocean physics and biology to particle flux in the deep ocean.

The OFP sediment traps collect from ten to a hundred grams of material during a typical two week sampling interval. Overall, the bulk composition of this material is remarkably consistent. About 70 percent of the sinking material at 3,200 meters consists of carbonaceous or siliceous shells of minute animals such as foraminifera, radiolarians, and pteropods, and the skeletal remains of single cell algae such as the coccolithophores, diatoms, and dinoflagellates. Although a few individual shells are large enough to sink unabated, most of the skeletal material consists of smaller particles and fragments that have been incorporated into larger, more rapidly sinking zooplankton fecal pellets or



The Oceanic Flux Program particle flux record in the Sargasso Sea. The present time series is today one of the very few oceanographic time series extending for more than a decade and by far the longest record of its kind.



Scanning electron micrographs of typical components of the particle flux material collected by the 3,200 meter Oceanic Flux Program trap. (A) A calcite shell of a foraminifer (a one-celled animal) with secondary calcite encrustations. The species composition and carbon and oxygen isotopic ratios of foraminifera shells preserved in ocean sediments are extensively used by paleoceanographers to reconstruct the past ocean environment. (B) A siliceous test of a radiolarian, another one-celled animal. (C) A zooplankton fecal pellet (left) and an unidentified biological aggregate. (D) Assorted skeletal remains of coccolithophorids, diatoms, dinoflagellates, and amorphous organic material aggregated inside the elongated fecal pellet shown in C. The elaborate round structures are individual calcite plates (liths) from different coccolithophore species.

Jeff Turner

amorphous biogenic material. Only about 12 percent of the material by weight is organic, as the majority (more than 95 percent) of organic material synthesized in the surface ocean is consumed before reaching the deep ocean. The remaining 18 percent of the trap material consists largely of clays and other minerals derived from atmospheric dust deposition and/or long range horizontal transport of resuspended ocean sediments.

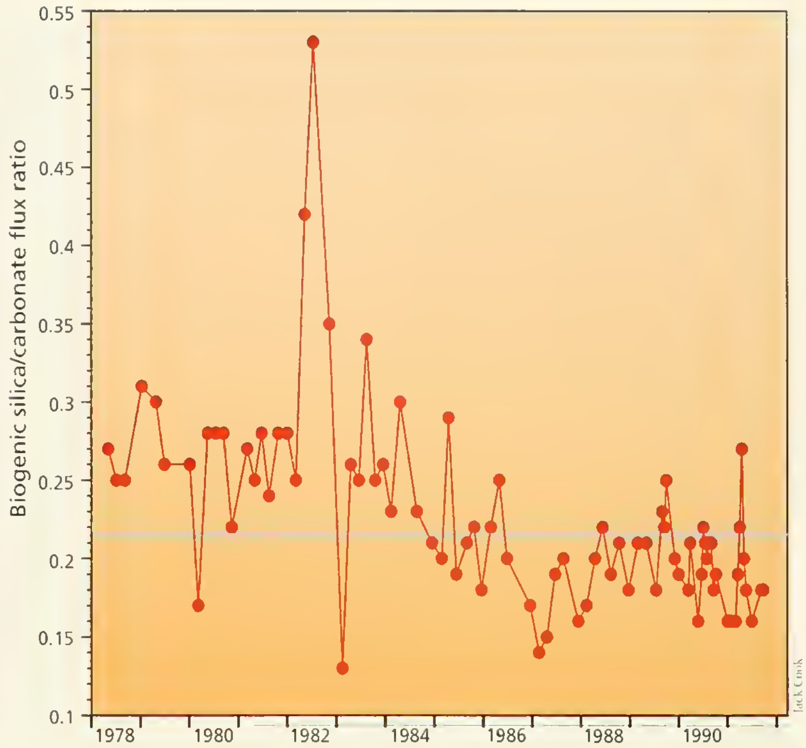
One intriguing finding is the existence of small, yet highly significant, long-term trends in the bulk composition of the sinking skeletal material at 3,200 meters. An overall 50 percent decrease in the biogenic silica to carbonate flux ratio from 1978 to 1991 is superimposed upon pronounced seasonal flux cycles of biogenic carbonate (synthesized by coccolithophorids and foraminifera) and silica (synthesized by radiolaria and diatoms). This decrease was due primarily to a reduction in the biogenic silica flux. The morphology of the siliceous particles changed during this period, suggesting that the species composition of silica-producing organisms in the overlying surface waters had changed. A significant (24 percent) increase in mean wind speed at Bermuda coincided with the change in deep biogenic silica flux. This led Deuser to hypothesize that small changes in physical forcing at the sea surface had induced significant changes in the surface ocean ecosystem, which in turn altered the makeup of export fluxes.

How do we relate what is captured in the sediment trap to the upper ocean processes that control vertical flux? Resident within the sinking material are inorganic and organic chemical signals that contain a wealth of information on the sources of the material and the subsequent processes that have influenced its flux. Often the flux pattern of a trace constituent may be drastically altered when one of the processes is varied, even though there is only an insignificant change in the bulk composition. We, and other researchers with whom we collaborate, analyze the OFP trap material for a variety of trace chemical constituents to unravel its history.

Our laboratory focuses on analysis of key organic compounds, or "biomarkers," using trace organic extraction methods, followed by gas chromatography and mass spectrometry, to identify and quantify nanogram (one-billionth of a gram) quantities of the target compounds in our samples. Recently, we analyzed the lipid (fatty organic) biomarker composition of trap material collected prior to, and during, an episodic flux "event" that occurred in January 1996 to determine the cause of this abrupt increase in flux. The lipid biomarker composition of sinking material collected just before the event indicated that this material was extensively degraded. However, the organic material collected during the high flux event was greatly enriched in labile (unstable) phytoplankton-derived biomarker compounds as well as in bacteria-derived biomarkers, indicating that it consisted of relatively fresh phytoplankton debris being actively degraded by bacteria. These biomarker results strongly suggest that this episodic high flux event resulted from a short-lived phytoplankton bloom in the overlying waters that was inefficiently degraded in surface waters and settled to depth rapidly. The persisting question is: How much of the observed increase in deep flux is due to increased production, and how much may be due to an increased efficiency of material transfer through the upper ocean?

Our findings suggest that the flux of labile, biologically available carbon and easily remineralized elements to the deep ocean underlying waters of low productivity may be more episodic than previously appreciated. At the OFP site, some of these events appear to be meteorologically driven by transient weather conditions affecting the influx of production-stimulating nutrients into the sunlit zone and the subsequent mixing of the resulting products into deeper waters. If this hypothesis proves correct, then changes in global climate should significantly affect export fluxes to the deep ocean—especially changes affecting wintertime storm patterns, such as the North Atlantic Oscillation (see *Oceanus* Vol. 39, No. 2).

What new insights from the OFP time-series can we expect in the future? The record to date shows subtle yet highly significant oceanographic trends against a background of large, and sometimes seemingly random, variability. Such trends can be detected only through continuous and carefully repeated measurements over a long period of time. To fully understand the multiyear and quasi-decadal cycles requires careful observation for perhaps an additional 20 years. As we progress in our long-term objective to assess interannual to decadal variability in material fluxes to the deep ocean, our goal is to interpret the temporal trends we observe in terms of changes in overlying ocean ecosystem functioning and in the atmosphere/climate system. This goal is of paramount importance for predicting the ocean's response to future, possibly anthropogenically induced, climate changes.



The long-term trend in the biogenic carbonate to silica flux ratio in the 3,200 meter Oceanic Flux Program trap. Variability in the deep particle flux appears to be forced by large scale changes in the atmosphere/ocean climate system.

The OFP time-series has been supported throughout by the National Science Foundation, with additional funding for the organic biomarker analyses from the Petroleum Research Fund.

Maureen Conte is an organic geochemist who uses trace lipid biomarker compounds to elucidate organic carbon pathways in the ocean and atmosphere. Before coming to WHOI in 1994 to succeed Werner Deuser as head of the Bermuda time series, she spent five cold and damp years in Britain, where she studied carbon cycling processes in the high latitude North Atlantic. She is also an accomplished musician who has traveled the US and Caribbean entertaining others with old-timey and Celtic melodies. When not in Bermuda (her home away from home) or working in the lab with research assistants Nate Ralph and JC Weber, she relaxes by paddling the quiet backwaters of the Cape and communing with the warty residents of her woodland frog pond.

Author Maureen Conte prepares to inject the extracted lipids of a trap sample into a capillary gas chromatograph. This instrument is used to separate and quantify up to a hundred different compounds present in a single complex mixture.

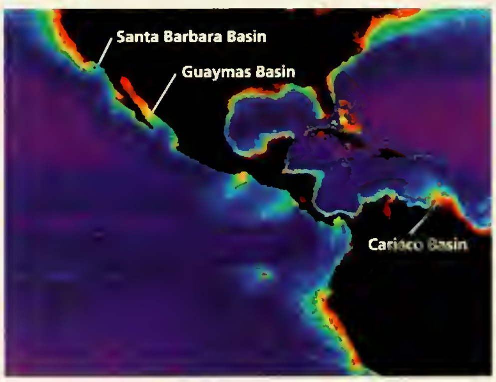
Scientists aboard R/V *Atlantis II* during a 1990 cruise deploy a sediment trap mooring in Guaymas Basin.

Continental Margin Particle Flux

Seasonal Cycles and Archives of Global Change

Robert Thunell
Professor of Geological Sciences and Marine Sciences, University of South Carolina

The boundaries between the oceans and the continents are dynamic regions for the production, recycling, and deposition of sedimentary particles. In general, rates of biological productivity along continental margins are significantly higher than in the open ocean. This is due to a variety of factors including coastal upwelling of nutrient-rich waters and nutrient input from continental runoff. While continental margins account for only about 10 percent of the global ocean area, 50 percent of the total marine organic carbon production is estimated to occur in this limited region, with much of it exported to the deep sea.



Eric Tappa

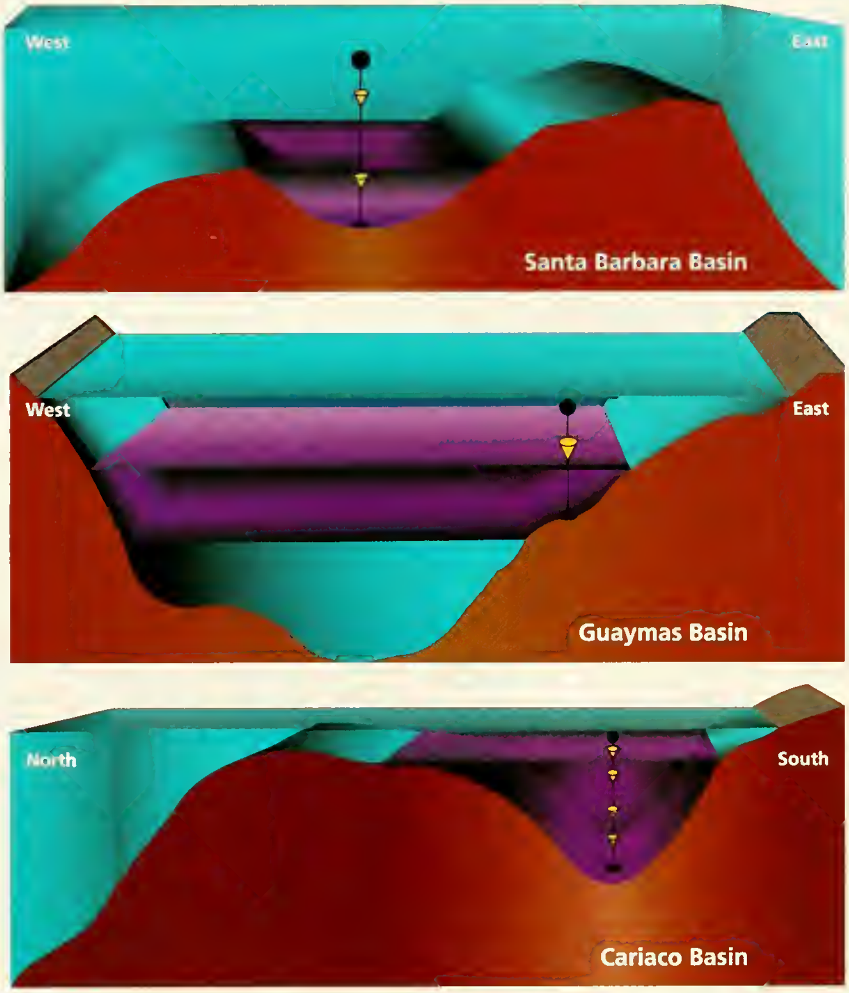
Composite surface ocean pigment concentration map derived from all Nimbus-7 Coastal Zone Color Scanner data acquired between November 1978 and June 1986. The pigment-rich coastal waters reflect the high productivity occurring in these regions and contrast sharply with conditions in much of the open ocean. The author's group is currently measuring particle fluxes in the three basins identified.

Despite the recognition that continental margins exert a strong influence on global biogeochemical cycles, there have been relatively few attempts to quantify either the magnitudes or nature of temporal variability in these regions' particle fluxes. In addition, the high sediment accumulation rates that characterize many continental margins make them ideal depositional settings for preserving high resolution records of past climate change.

In the summer of 1990 my University of South Carolina colleagues (Eric Tappa, Carol Pride, Eileen Kincaid, and Kathy Tedesco) and I initiated the first of three time series sediment trapping programs designed to study particle fluxes in continental margin basins. The basins we selected for study include Santa Barbara Basin (offshore California), Guaymas Basin (Gulf of California), and Cariaco Basin (Venezuelan margin). All three field programs are currently ongoing, with the Guaymas Basin project now in its eighth year. The work in Cariaco Basin is part of a large international effort entitled CARIACO (CArbon Retention In A Colored Ocean) involving researchers from other US and Venezuelan institutions. At all three locations, we are fortunate to have local marine labs that provide much needed logistical and ship support. They are the Southern California Marine Institute (Los Angeles), Estacion de Investigaciones Marinas de Margarita (Isla de Margarita, Venezuela), and CIB (Guaymas, Mexico).

These basins share a number of common features. All three are sites of seasonal, wind-driven coastal upwelling and high primary productivity. Additionally, all three basins are marked by oxygen-depleted conditions (see figure). The Cariaco and Santa Barbara basins are separated from regions farther offshore by sills that isolate the deep waters in the basins and cause them to become anoxic. The situation in the Guaymas Basin is somewhat different, in that the oxygen-depleted waters occur in mid water column and are associated with Pacific Intermediate Water that flows into the Gulf of California at depths between 500 and 1,000 meters. In all three basins, sediments accumulate in clearly defined layers within the anoxic zones due to the absence of benthic organisms and the consequent lack of bioturbation. A pair of these "laminae," referred to as a varve and consisting of one dark layer and one light layer, represents a year of deposition in each basin. Such sediments serve as natural archives for studying annual- to decadal-scale changes in past climatic conditions.

The basic objectives of the sediment trapping programs in all three basins are similar. First, we document seasonal to interannual changes in sediment fluxes and then relate this variability to changing hydrographic and climatic conditions. Second, we use the observed seasonal variability in the fluxes of different sediment types to develop models of varve formation for each basin. Finally, we identify and calibrate the best proxies for studying climate change in each basin and then apply these to sediment cores in order to reconstruct records of past climate change. In addition, for the Cariaco Basin study we are using an array of sediment traps placed throughout the water column to measure changes in carbon flux with depth. This allows us to evaluate whether anoxia results in enhanced preservation of organic matter.

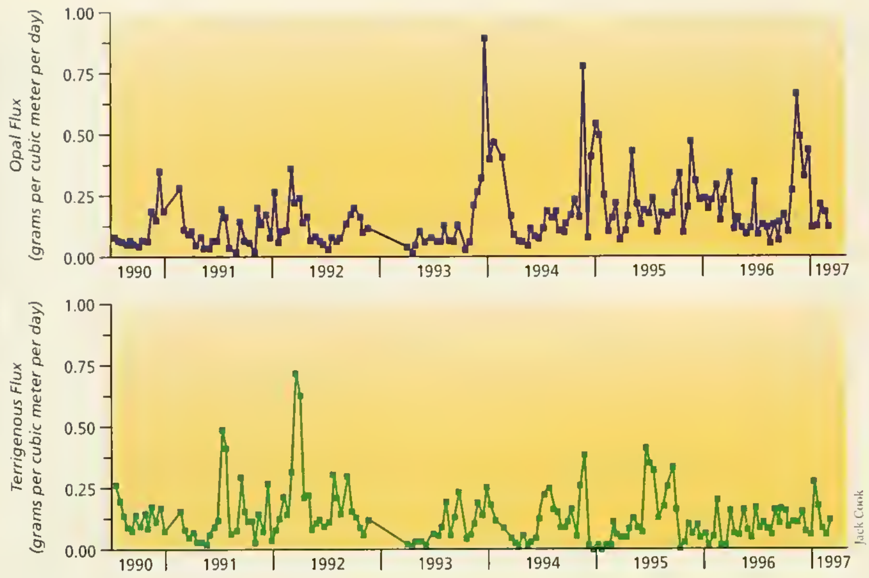


Eric Tappa

Cross-sections of the Santa Barbara, Guaymas, and Cariaco Basins showing the configuration of the sediment trap moorings. The region of anoxic conditions in each basin is indicated by purple shading. It is beneath these oxygen-deficient zones that laminated sediments are preserved.

Changes in wind intensity and/or direction are the primary physical forcing mechanisms responsible for seasonal variability in the production and flux of sediments in all three locations. In Santa Barbara Basin the winds are predominantly from the north and are strongest during the spring and early summer, with the most intense upwelling of deep waters occurring during this period. Coastal upwelling in Cariaco Basin is associated with

Biogenic opal (blue) and terrigenous material (green) flux records from Guaymas Basin for the period July 1990 through March 1997 reflect seasonal and interannual changes in climatic conditions. The high opal fluxes are generally associated with the late fall to early spring period of high primary productivity, while terrigenous fluxes are usually high during the summer rainy season.

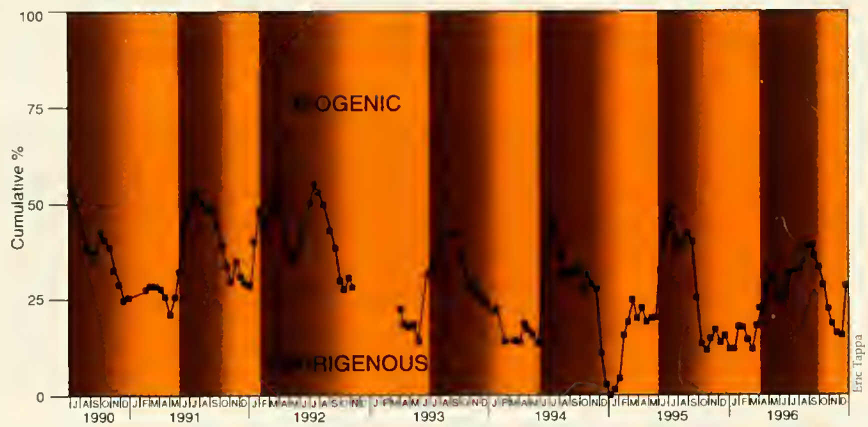


seasonal changes in the position of the Intertropical Convergence Zone (ITCZ) and the strength of the Trade Winds. In the winter and spring, the ITCZ is in its most southerly position, close to the equator, resulting in strong easterly winds and upwelling along the Venezuelan coast. The Gulf of California usually experiences a seasonal change in wind direction in November, when there is a reversal from southerly to northerly winds, causing upwelling and high productivity from late fall to spring.

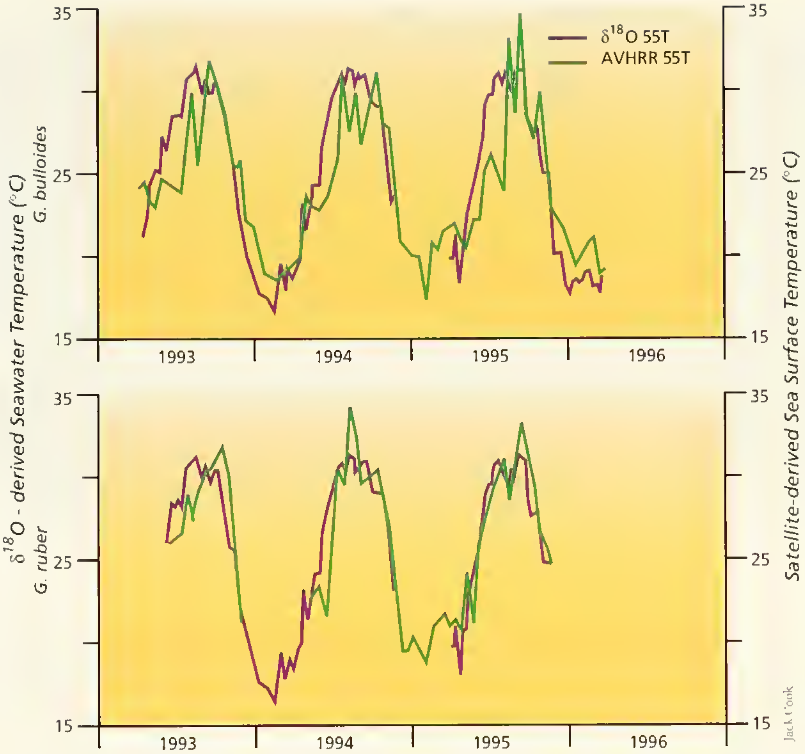
I use our results from the Guaymas Basin to illustrate the relationship between seasonal changes in sediment fluxes and climate forcing. First, it should be pointed out that diatoms are the dominant group of plankton in the Guaymas Basin. Since these organisms produce shells made of opaline silica, this is the most abundant biologically produced sediment in the region. The other major component of the total sediment flux in Guaymas Basin is terrigenous material delivered to the basin from surrounding land masses. Together, opal and terrigenous material account for about 75 percent of the total particle flux in Guaymas Basin. The flux time series for these two sediment types for the period July 1990 through December 1996 reveals distinctive, recurring seasonal patterns (see figure). Each year there is a rapid increase in opal flux in late fall, in direct response to the switch to northerly winds. These winds cause nutrients to be mixed to the surface, and a diatom bloom results. In contrast, the highest fluxes of terrigenous material tend to occur during the summer rainy season. According to Tim Baumgartner (Scripps Institution of Oceanography), most of this material comes from the Sonoran Desert and is atmospherically transported to the basin during thunderstorms.

The six-year time series also displays some interannual variability. For example, opal fluxes from late fall 1991 to spring 1992 are not nearly as high as those recorded for the same time period in subsequent years. Shortly after we began the Guaymas Basin project in summer 1990, El Niño conditions developed in the eastern Pacific and reached their peak in late 1991/early 1992. During El Niño events the strength of the northerly winds blowing down the Gulf of California is diminished and unusually warm equatorial Pacific surface waters migrate northward into the gulf. These conditions suppress mixing of the surface layer and result in lower than normal diatom production.

The alternating light and dark laminae accumulating in all three basins result from seasonal changes in the composition of the material being delivered to the seafloor. Our Guaymas Basin time series clearly illustrates these seasonal changes in basic sediment type as well as how we envision this variability translates into the formation of sediment laminae (see figure). The light laminae, which consist mostly of low density plankton remains, particularly diatoms, are deposited during times of upwelling and high productivity. In Guaymas and Cariaco Basins, the light laminae form from winter to spring, while in Santa Barbara Basin these units represent deposition during the spring and summer. The dark laminae are denser and consist mostly of terrigenous material transported to each of the basins during their rainy seasons—winter in



Changes in the relative proportions of biogenic material and terrigenous material in the total sediment flux for Guaymas Basin. These seasonal changes in the composition of the sediment flux result in the deposition of laminae on the seafloor. The high flux of biogenic material from late fall through spring produces the light laminae. In contrast, dark laminae form during the summer when the sediment flux carries high concentrations of terrigenous material.



A comparison of satellite measured sea surface temperatures for Guaymas Basin and temperatures estimated from the oxygen isotopic composition of two species of planktonic foraminifera, *Globigerina bulloides* and *Globigerinoides ruber* collected in sediment traps. The good agreement between the observed and estimated temperatures indicates that the oxygen isotopic composition of shells of these species of foraminifera preserved in the sediments can be used to estimate past sea surface temperatures in the Gulf of California.

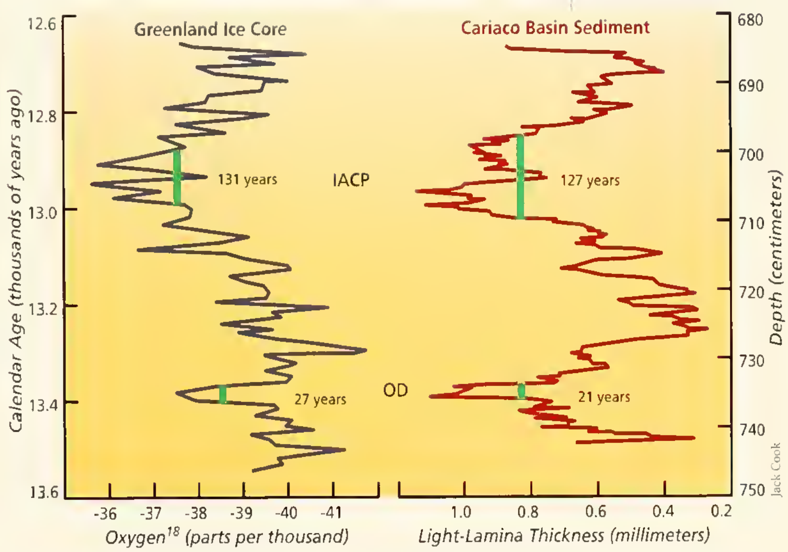
the Santa Barbara region and summer in both Guaymas and Cariaco Basins. Thus, each of these layers contains clues about prevailing climate conditions during different times of the year in each of these regions.

Our challenge is to develop the best tools for extracting this climate information from the sediment record. These include biotic, geochemical, and sedimentological proxies of different ocean properties. For example, besides diatoms, other groups of plankton produce shells that accumulate on the seafloor. One such group, the planktonic foraminifera, secrete calcium carbonate shells and have been used extensively to reconstruct paleoclimate conditions. Carol Pride from the University of South Carolina has been studying several species of planktonic foraminifera collected in our Gulf of California sediment traps in an effort to determine how well the oxygen isotopic composition of their shells records the water temperature at the time of their growth. She has found that the isotopic composition of two species, *Globigerina bulloides* and *Globigerinoides ruber*, accurately records sea surface temperature changes in Guaymas Basin (**see figure**). With this observation, we now have a tool for deciphering the past history of sea surface temperature changes in the Gulf of California.

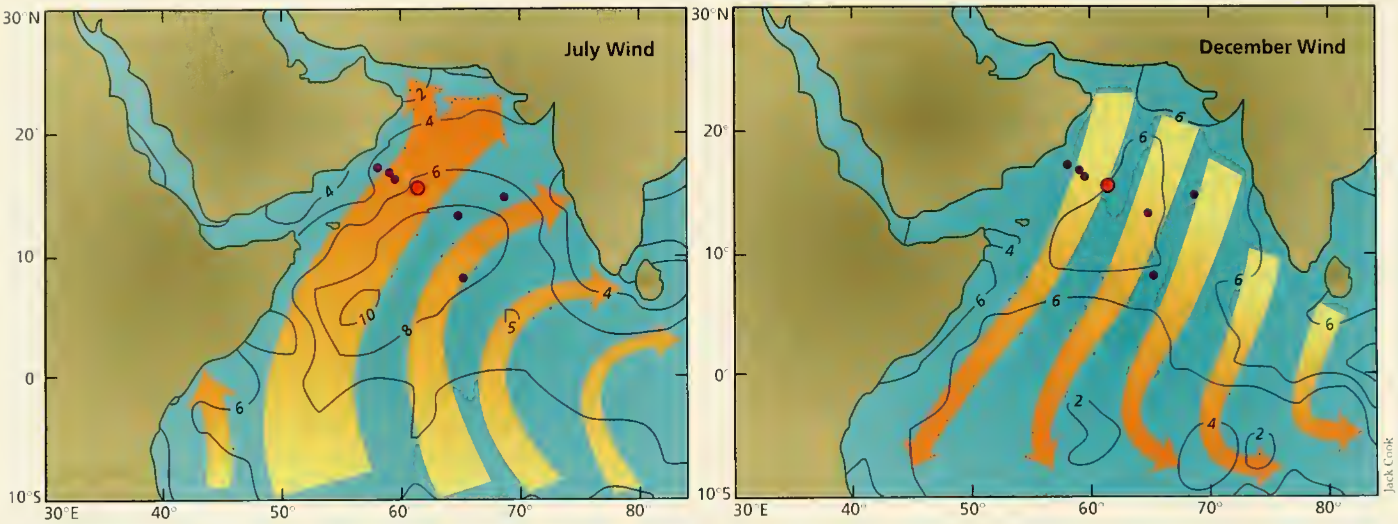
It is now widely recognized that these anoxic, continental margin basins provide high resolution climate records that are unequaled in the marine realm. The recent work of Konrad Hughen (University of Colorado) on Cariaco Basin sediments provides an excellent example of the high resolution records that can be obtained from laminated sediments. By measuring the thickness of individual light lamina and using this as a proxy for past changes in productivity, Hughen and colleagues were able to relate annual- to decadal-scale variability in productivity in Cariaco Basin to changing climate conditions during the last deglaciation. Finally, in the last several years, the Ocean Drilling Program has cored both the Santa Barbara Basin and the Cariaco Basin, and many researchers are actively studying the climate histories preserved in these sediment records.

The continental margin sediment trap work has been supported by the National Science Foundation Division of Ocean Sciences and the National Oceanic and Atmospheric Administration Office of Global Programs.

Bob Thunell has served as Chair of the University of South Carolina Department of Geological Sciences for the past nine years. His first foray into the sediment trap/particle flux game came in 1978 when he was a postdoctoral scholar at WHOI and had the good fortune to work with Sus Honjo. Since moving to South Carolina in 1979, Bob has become an avid Gamecock fan and makes sure to schedule his cruises so they don't interfere with football games. In his "spare time," Bob runs a taxi service that transports his three sons to soccer tournaments, basketball games, and swim meets.



Comparison of a Greenland ice core oxygen isotope record and a record of the thickness of light laminae in a Cariaco Basin sediment core for the period 13,600 to 12,600 years ago. The oxygen isotope record provides information on changes in atmospheric temperature over Greenland, while the light-lamina thickness is a function of changes in productivity along the Venezuelan continental margin. The pattern of change in both records is very similar, with high productivity (thicker light laminae) occurring during periods of climatic cooling (lower oxygen isotope values).



The surface winds and ocean mixed layer depths in the Arabian Sea in July (left) and December (right). The depth of the mixed layer, the upper layer that is well-stirred by surface forcing, is shown in meters. The strong surface winds of the Southwest Monsoon are evident in July, and the moderate winds typical of the Northwest Monsoon blow in December. The locations of the surface Air-Sea Interaction (ASI) and sediment trap moorings are marked by red and dark blue dots respectively.

Monsoon Winds and Carbon Cycles in the Arabian Sea

Susumu Honjo
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Robert A. Weller
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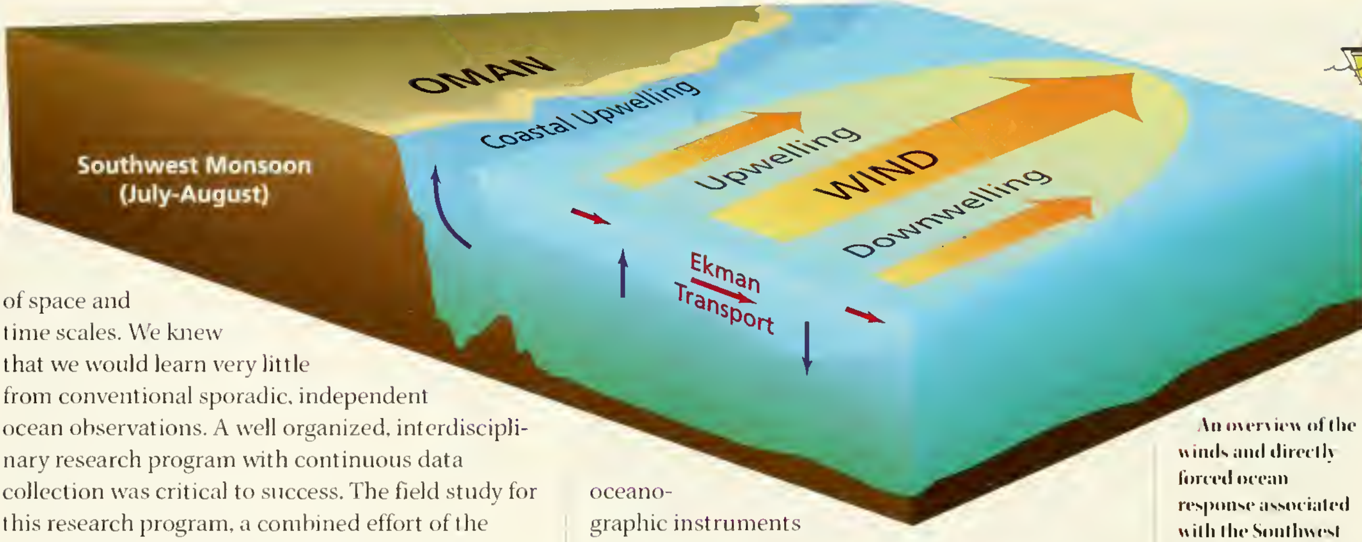
The monsoon, a giant sea breeze between the Asian massif and the Indian Ocean, is one of the most significant natural phenomena that influences the everyday life of more than 60 percent of the world's population. In summer, heating of the land produces a region of intense low surface pressure over northwestern India, Pakistan, and northern Arabia. A broad region of southwesterly winds develops, quite different from the northeast trades found in the other oceans at the same latitudes. The elevated east African coastline intensifies the wind near the surface and directs it parallel to the coasts of Somalia, Yemen, and Oman. This strong flow, the Findlater Jet, is remarkable for its steadiness of direction and its strength, which can exceed 36 knots in July. The offshore Ekman transport (see figure opposite) that results gives rise to intense upwelling along the coast, where cold, nutrient-rich water is brought up to the surface, and to convergence and downwelling in the central and eastern part of the Arabian Sea. In response to the Southwest Monsoon and unlike conditions in any other ocean, the surface mixed layer in the central Arabian Sea deepens and cools during the summer. In midwinter, when the Eurasian continent cools, a high pressure region develops on the Tibetan plateau and northeast winds persist over southern Asia and the Arabian Sea. These winds are not as strong as during the summer, but, combined with strong surface cooling, they lead to deepening of the mixed layer in the central and western Arabian Sea together with higher primary production over the entire Arabian Sea. Thus, the winter monsoon brings a second cycle of mixed layer deepening and cooling to the Arabian Sea.

Even at it coolest, however, the surface water of the Arabian Sea is relatively warm, about 25°C in the central Arabian Sea, and the strong sunlight found year-round in low latitudes can support high productivity in the upper ocean. Thus, nutrient availability is the limiting factor, and primary productivity depends largely on mixing processes that can bring nutrient-rich water to the surface from below. The objective of our work in the Arabian Sea was to understand this link between the physics of the ocean's response to the monsoon and the biological and geochemical variability of the Arabian Sea. Our data show that nutrients brought to the surface by mixing drive productivity in the surface layer, which produces particulates that fall from the surface layer into the deep ocean, removing carbon dioxide (CO_2) from the air to that "sink" region.

The task of observing this biological pump is not easy; the ocean is highly variable, with a wide range



Jack Cook

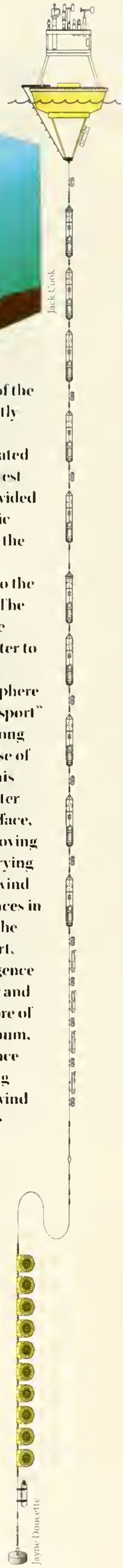
An overview of the winds and directly forced ocean response associated with the Southwest Monsoon is provided by this schematic cross-section of the ocean taken perpendicular to the coast of Oman. The jet of the surface winds drives water to its right in the northern hemisphere as "Ekman transport" (red arrows). Along the coast because of the boundary this leads to cool water rising to the surface, or upwelling. Moving offshore, the varying strength of the wind leads to differences in the strength of the Ekman transport, causing a divergence of surface water and upwelling inshore of the wind maximum, and a convergence and downwelling offshore of the wind maximum (blue arrows).

of space and time scales. We knew that we would learn very little from conventional sporadic, independent ocean observations. A well organized, interdisciplinary research program with continuous data collection was critical to success. The field study for this research program, a combined effort of the Joint Global Ocean Flux Study (JGOFS) program and the US Office of Naval Research, began in late 1994 and continued for about one year. It featured observations during all phases of the monsoon, including seven repeated occupations of a cruise track with numerous stops to sample the ocean in detail. In addition, several advanced, moored instrument systems were deployed for the duration to sample the changing Arabian Sea environment continuously, hour-by-hour, at all depths.

In the lull after the summer monsoon of 1994, the Upper Ocean Processes Group of the Woods Hole Oceanographic Institution deployed an advanced surface mooring in the western, central Arabian Sea where the Findlater Jet is strongest. This Air-Sea Interaction (ASI) buoy carried a complete meteorological station as well as an unprecedented number (32) and diversity of oceanographic instruments for measuring temperature, salinity, current, dissolved oxygen, chlorophyll fluorescence, light transmission, and photosynthetically available radiation. This instrument complement resulted from a collaboration of investigators at WHOI, the University of Santa Barbara (Tommy Dickey), and the Lamont-Doherty Earth Observatory (John Marra and Chris Langdon). This buoy was recovered in the spring of 1995 and a fresh set of equipment deployed at the same site until October 1995 in order to collect a full year of data. During the experiment, the meteorological data was telemetered via satellite and published on a World Wide Web site to be immediately accessible by researchers worldwide.

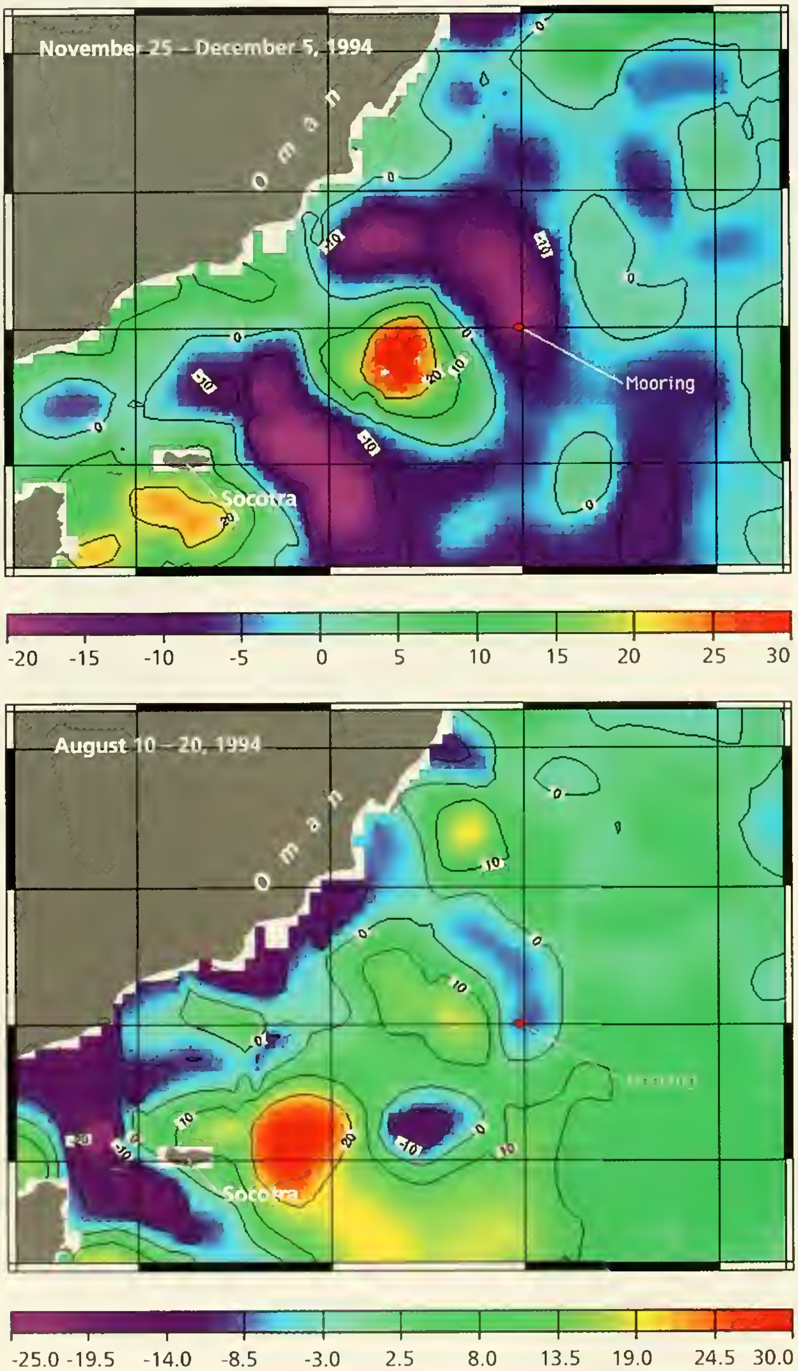
We also deployed in the 4-kilometer-deep ocean a mooring with three time-series sediment traps at depths of 0.8 kilometers, 2.2 kilometers, and 3.5

Robert Weller



Jayne Doucette

The Air-Sea Intraction (ASI) mooring buoy is equipped with two sets of meteorological sensors to measure wind speed and direction, air and sea temperature, incoming shortwave and longwave radiation, barometric pressure, relative humidity, and rain. Current meters and other instruments are located along the mooring line beneath the ASI buoy (see drawing at right). Arabian Sea sediment trap moorings were similar to the drawing on page 9.



Sea surface height, as measured by a satellite altimeter. The height of the sea surface reflects the geostrophic current field associated with large eddies. These eddies form off the Horn of Africa, near the island of Socotra, during the height of the Southwest Monsoon and later drift to the northeast. The strong currents with slowly varying directions seen in May and September in the figure opposite are associated with the passage of these large eddies through the array of moorings.

kilometers. Located about 53 kilometers north of the ASI mooring, these instruments were part of an eight-mooring (24-time-series-sediment-trap) Arabian Sea network fielded by US, German, and Indian scientists during 1994 and 1995. All the sediment traps were set to open and close their collecting bottles at precisely the same time: every eight and a half days a new sample bottle automatically moved into place.

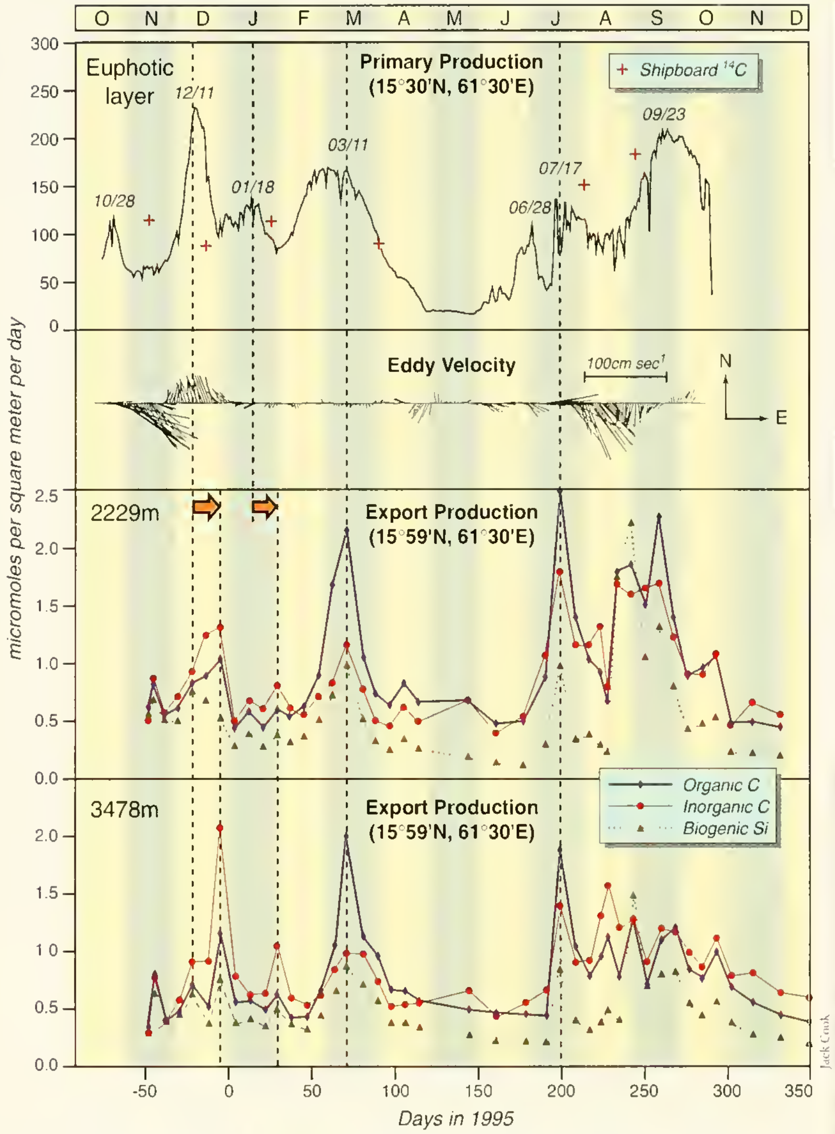
Data from the moorings confirmed our suspicion that productivity in the upper ocean was episodic rather than slowly varying as had been assumed for decades. Tommy Dickey and John Marra's time series of chlorophyll content from their instruments on the ASI mooring showed that most of the annual primary production occurred during four phytoplankton blooms (see figure opposite). Sediment trap data showed that particle flux to the deep interior of the ocean was also strongly episodic—timing as well as relative amplitudes of the increased particle flux closely followed the primary production blooms, offset by several days to a few weeks. In other words, the biological pump in this central Arabian Sea site works hard several times a year rather than operating continuously at a moderate rate. At this location, the biological pump transfers slightly less than one percent of the photosynthetically assimilated organic carbon to the ocean's interior for long-term storage of CO_2 carbon.

These findings have a number of important implications that are applicable to a more general understanding of the ocean. Conventional seagoing productivity measurements in a given ocean area have simply been too scarce to allow us to develop a description of the annual variability in primary production in much of the open ocean. Even the unprecedented, repeated ship survey in the Arabian Sea is hard-pressed to resolve the short, intense blooms seen in the moored time series.

As the figure opposite shows, the day-to-day variability of the primary productivity estimated from Dickey and Marra's instruments coincides strikingly with that of organic and inorganic carbon flux documented by the time series sediment trap array. By comparing the timing of events that occurred in the eupohotic layer with events in the deep ocean layers, we can determine the settling rate of carbon-carrying particles. We previously suspected that the sinking speed of carbon particles falling from the upper ocean is much faster than what had been estimated from Stoke's law, which provides a relation between fall rate and the drag on particles in water. Our Arabian Sea results confirm this important hypothesis about the vertical transport of organic carbon in the ocean's water column. The consequences of the short-lived primary production maximum of December 11, 1994, are evident in the 2.2-and 3.5-kilometer-deep sediment traps, whose sampling period centered on December 29. Settling carbon particles arrived at those depths two 8.5-day sample intervals after the maximum organic carbon production near the surface. However, during the December 7 to 16 open period, the biogenic silica export maximum (mostly from diatom frustules) appeared in the ocean's interior earlier than the organic carbon export maximum. The large organic carbon export event that peaked during the March 11 to 19 open period corresponded to the primary production bloom that peaked on March 11 (though this was not as sharp as the December 11 peak). This indicates that the particulate organic carbon that escaped remineralization reached a depth of 3.5 kilometers within one 8.5-day interval.

During the summer monsoon, the primary production bloom that peaked on July 17 was modest compared to the very large export production event that peaked during the July 17 to 25 sampling interval. A small primary production maximum that peaked on June 28 was not seen clearly in the export flux, but the signal may have blended with the July 17 peak.

The last and largest productivity event of the 1995 summer monsoon began in late August and continued for nearly two months. The organic carbon export production maximum at 2.2 kilometers depth occurred during the September 14 to 22 period, earlier than that of the primary production maximum on September 23.

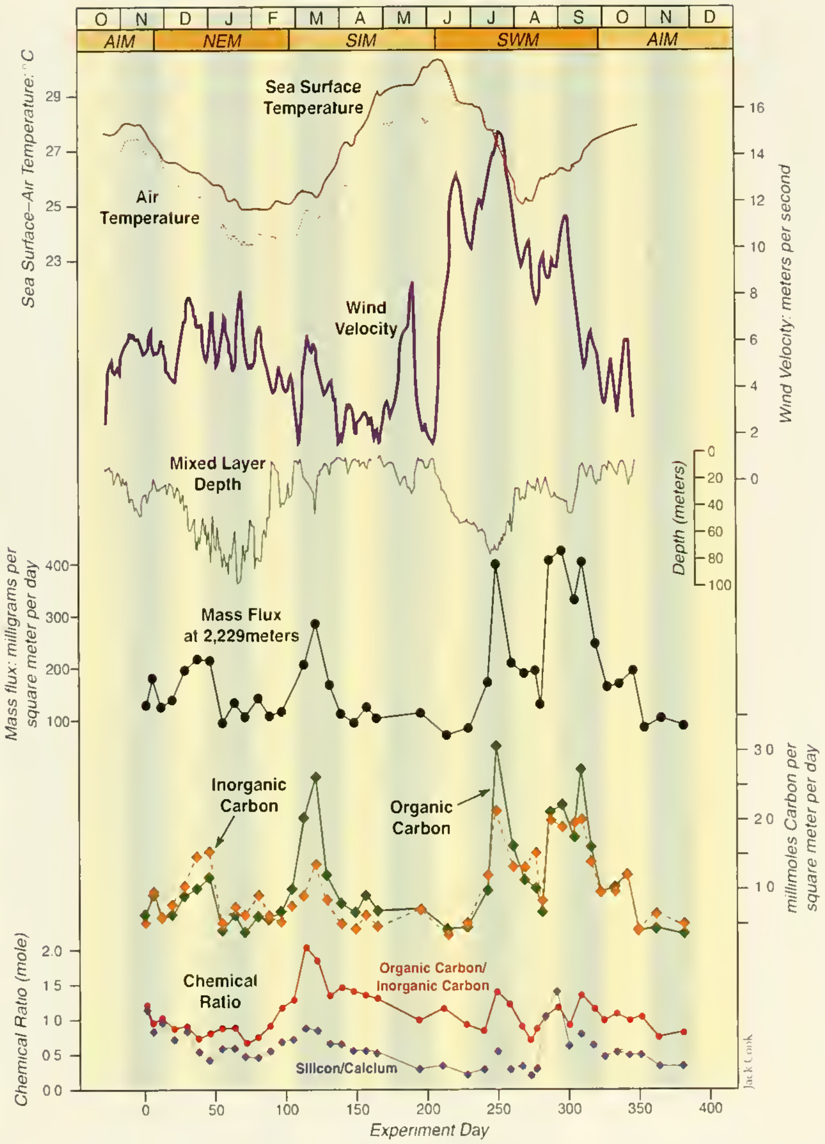


Time series plots from the surface mooring and nearest sediment trap mooring. Peaks in the variability in primary production (top), based on the measurements on the surface mooring by Dickey and Marra correlate well with peaks in the export production (lower two) measured by the sediment traps at 2,229 and 3,478 meters. Note the correlation as well between the strong currents (second from top) measured by the surface mooring during export production peaks in May and September. These peaks in velocity were associated with the passing eddies.

Thus, we have found the chemical signatures of large bloom events in the euphotic layer to be preserved in exported particles collected in the ocean's interior. The production rate as well as the timing of the bloom is duplicated. Diatom production is a good indicator of the ocean's fertility and the biological pump's efficiency. When conditions that we refer to as "Silica Ocean" prevail, the biological pump functions more efficiently to remove CO_2 carbon from the atmosphere; a Silica Ocean produces more diatoms than coccolithophorids at the initial stage of the biological pumping (see article on page 4). The tropical Arabian Sea is more often a "Carbonate Ocean." However, during the observed periods of high primary production, this sea temporarily becomes a "Silica Ocean," resulting in transport of more CO_2 carbon to the deep ocean sink.

Various physical processes may be involved in the biological pump. Priming the pump requires that nutrient rich water from below the surface layer be brought up into the euphotic region. Near the coast, upwelling does this. In the central Arabian Sea, the mixed layer deepens and cools primarily due to wind-driven entrainment of cooler, nutrient rich water across its base in the summer monsoon. In the winter monsoon, the surface water in the central Arabian Sea is made more dense (cooler and saltier) by surface cooling and evaporation. The dense water sinks and the layer deepens with only modest mixing across its base.

However, another finding of this work leads us to consider different physical processes as well. That finding stems from our observations that the abundance of biologically assimilated silica relative to the calcium carbonate material collected in the sediment traps varies. In practice, we often use the ratio of biologic calcium to silicon found in the flux and/or the ratio of organic carbon (from settling cell material) to inorganic carbon (from settling biogenic calcium carbonate) to quantify this ratio. We observe that the silicon to calcium ratio in the particles exported to the ocean's interior in blooms in December 1994 and August 1995 was very high



Time series plots from the surface mooring and the 2,229 meter sediment trap. The sea surface and air temperature (upper plot) show the cooling that occurs during both the northeast monsoon and the southwest monsoon. The modest winds of the northeast monsoon together with loss of heat from the ocean to the atmosphere lead to deepening of the mixed layer (third plot down) in December and January. The deepening of the mixed layer in June and July during the southwest monsoon results from mixing driven by the very strong winds. The mass flux and carbon flux time series (fourth and fifth down) track the export production seen in the figure on page 27. Time series of the ratios of chemical species in the 2,229 meter trap, organic to inorganic carbon and silicon to calcium, and of the flux of inorganic and organic carbon (bottom) indicate that the chemical signatures vary with wind velocity (positive relationship) and mixed layer depth (negative relationship). The authors are intrigued by the variability and the possibility of linking it to the physics of the mixing that brings nutrients to the surface.

and that during these periods eddies were passing the mooring site. One apparent impact of these eddies is the introduction of nutrient rich water into the surface layer. The strong surface currents associated with these eddies were seen by the current meters on the ASI mooring. The eddies also have a sea surface elevation signature, and Tommy Dickey was able to correlate the passage of particular large eddies observed by satellite with the blooms he and Marra observed at the ASI mooring.

In the euphotic layer of the Arabian Sea, dissolved silica is depleted by the demands of organisms living in the upper ocean layers. As soon as the dissolved silica is supplied from deeper layers to the euphotic layer, diatom production accelerates. In the Arabian Sea, production of coccolithorphorids also increases, but diatom production dominates. The primary production blooms of February–March and July 1995 were not linked to eddies, but were locked to the end of the periods of mixed layer deepening associated with each monsoon. There is also evidence that a dust storm caused by the strong winds in July 1995 covered the entire western and central Arabian Sea coincident with the July bloom. The ratio of organic carbon to inorganic carbon stood out from the background; but while the silicon to calcium ratio in the particles arriving at the ocean's interior during these blooms was high, it was not as elevated as that seen during the eddy-related blooms.

Thus, perhaps one of our most intriguing results is that the chemical composition of what we find to be the rapid export flux from the surface layer may guide our efforts to understand the physics of the Arabian Sea. Convective deepening and wind-driven entrainment appear to result in only modest transport of nutrient-rich water into the surface layer compared to the eddy-related transport. We will now have to consider more carefully the role of eddies. By doing so we will build our understanding of how the biological pump now functions and be able to apply that understanding to the record of how the pump functioned in the geological past as revealed in the records provided by the ocean sediments (see Paleoclimate article on page 11).

Sus Honjo's work was supported by the National Science Foundation, and Bob Weller's by the Office of Naval Research. The data and other contributions to their understanding provided by colleagues, particularly Tommy Dickey and John Marra, is gratefully acknowledged.

Sus Honjo's biography may be found on page 7.

Bob Weller is part of the Physical Oceanography Department's Upper Ocean Processes Group. The talent and skill of this group's technical staff have made it possible to deploy heavily instrumented surface moorings around the globe and to make significant progress toward understanding the interaction of the ocean and atmosphere. His most recent experimental project deployed two surface moorings in the eastern tropical Pacific as part of the Pan American Climate Study. In 1997, this put Bob and the rest of the group at sea and away from WHOI for six weeks in April and May on a Lima, Peru, to San Diego cruise aboard Roger Revelle *(Scripps Institution of Oceanography) and again for six weeks in November and December on a Honolulu to Honolulu voyage on* Thomas Thompson *(University of Washington).*

Geochemical Archives Encoded in Deep-Sea Sediments Offer Clues for Reconstructing the Ocean's Role in Past Climatic Changes

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Michael P. Bacon
Chairman and Senior Scientist, Marine Chemistry and Geochemistry Department

Paleoceanographers are trying to understand the causes and consequences of global climate changes that have occurred in the geological past. One impetus for gaining a better understanding of the factors that have affected global climate in the past is the need to improve our predictive capabilities for future climate changes, possibly induced by the rise of anthropogenic carbon dioxide (CO_2) in the atmosphere.

The relatively recent geological past (the last 1.6 million years), known as the Quaternary period, is characterized by large climatic swings from ice age to warmer interglacial periods similar to the present one. During the ice ages, large ice sheets accumulated on the northern continents, and sea level dropped by as much as 120 meters. Analysis of air bubbles trapped in the Antarctic and Greenland ice caps documents significantly lower atmospheric CO_2 levels during the cold glacial periods compared to the warm interglacials (Fig. 1). Since carbon dioxide is a well known "greenhouse" gas, whose presence in the atmosphere traps heat near the earth's surface, its lower concentration in the glacial atmosphere could have contributed to the cold climate of the ice ages.

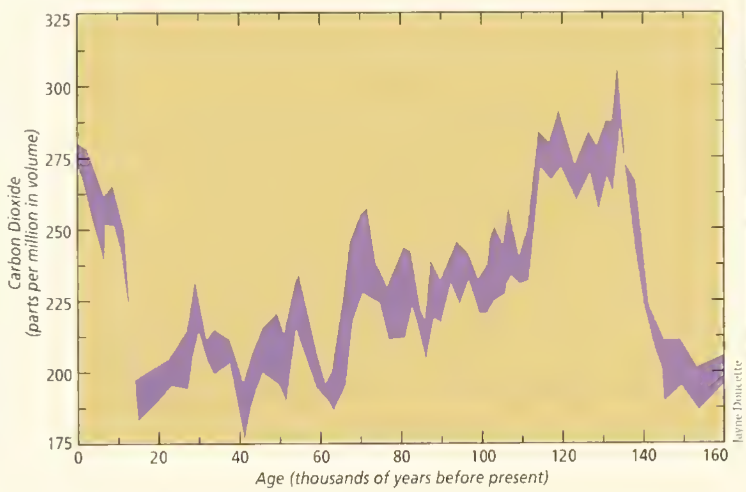


Figure 1: Changes in atmospheric carbon dioxide during the last 150,000 years recorded by the carbon dioxide content of air bubbles trapped in ice that accumulated on Antarctica.
(Barnola, J.-M., D. Raynaud, Y. S. Korotkevitch, and C. Lorius (1987) Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* 329, 408-414.)

Establishing the exact role that atmospheric CO_2 played in past natural climatic oscillations, however, is not a simple matter. Changes in atmospheric CO_2 may have been more a response to climate change than a forcing mechanism. On the other hand, while we know that the pace of Quaternary glaciations was primarily driven by variations in Earth's distance from the sun and in the angle of Earth's axis of rotation, the resulting changes in incoming solar radiation to the planet's surface are too small to account for the large climate variability observed. This implies that the effect of these orbital parameters must have been amplified by some internal feedback mechanisms within the earth's environment, and we suspect that atmospheric CO_2 may be a major factor. In view of its obvious connection to present societal concerns, this particular problem has elicited a lot of attention in the paleoceanographic community.

In the modern ocean, factors affecting atmospheric CO_2, such as export flux of organic carbon and carbonate to the deep sea, dissolution of calcium carbonate shells in the deep sea, and deep water circulation, can be measured directly. A variety of incubation techniques are used to measure production of organic matter in surface waters, and broad views of surface water production at a given time can now be obtained from satellite imagery (Fig. 2). As several articles in this issue attest, sediment traps are deployed to estimate the export and recycling of organic matter and calcium carbonate from surface waters to the deep sea, and thermohaline circulation is becoming increasingly well constrained, both in terms of flow rates and pathways (see *Oceanus* Vol. 37, No. 1 and Vol. 39, No. 2). For past oceans, however, these variables cannot be measured directly but must be inferred from proxy analysis (a marker in the sediments from which the variables can be inferred indirectly). A fraction of the biogenic particles produced in surface water survives degradation or dissolution in the deep sea and gradually accumulates on the seafloor. As many oceanic processes leave a chemical imprint in this material, a very complex but rather comprehensive chemical archive, which can be dated and deciphered, is continuously buried in deep-sea sediments.

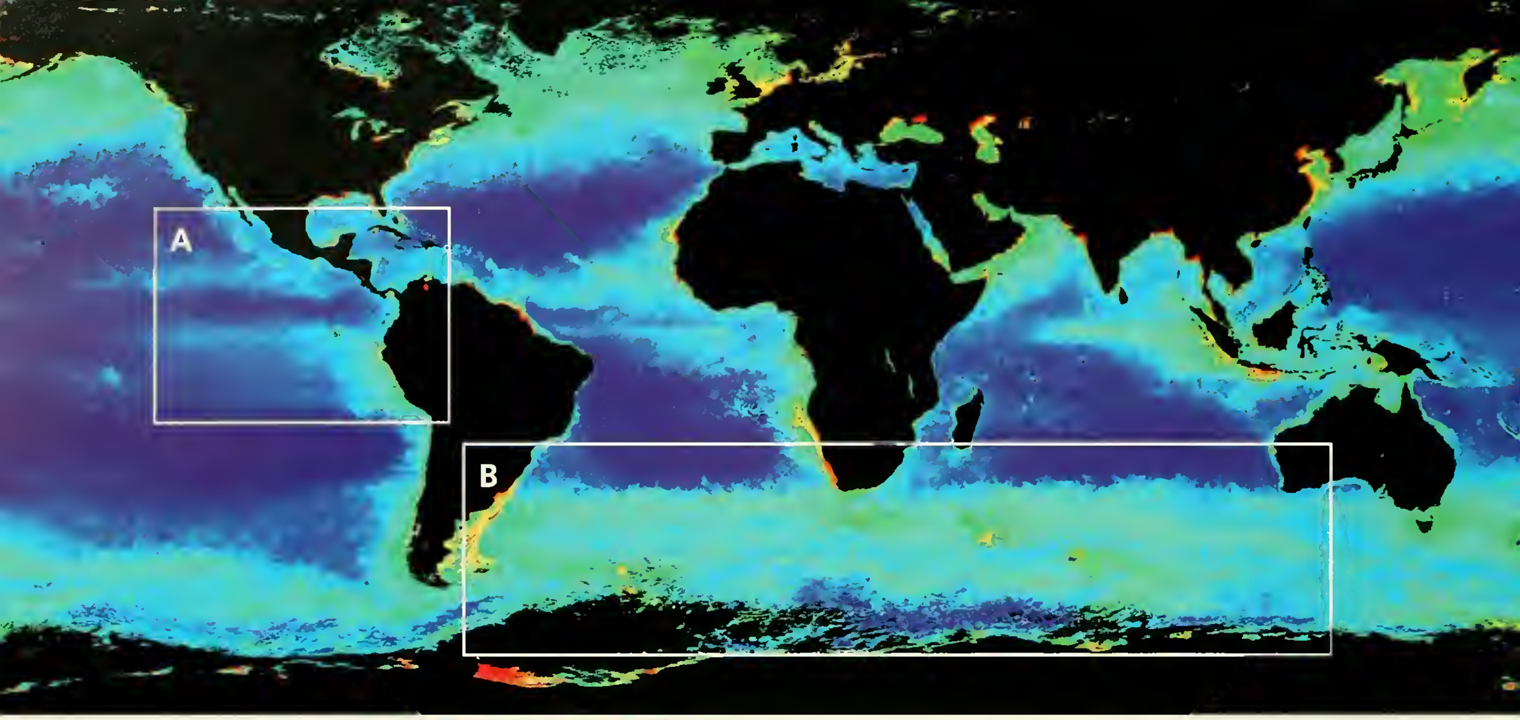


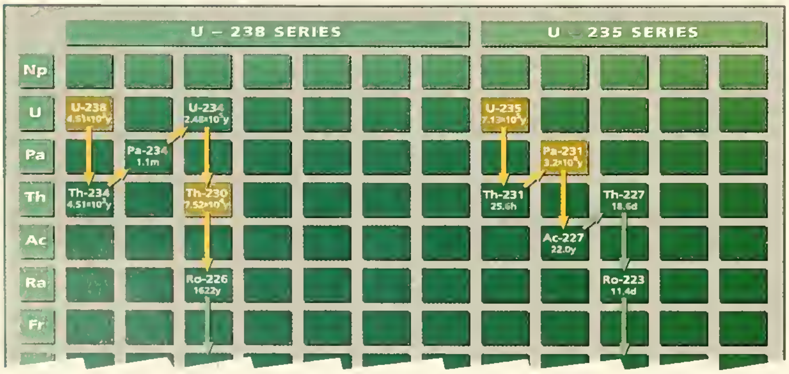
Figure 2: Ocean color measured by satellite. In the tropical open ocean, productivity is comparatively low due to permanent thermal stratification of surface waters that limits the supply of nutrients from deeper waters. The resulting flux of biogenic material to the deep sea is also low. In contrast, in the more productive regions of the ocean, abundant phytoplankton sustain much larger sinking fluxes of biogenic material. These regions are most prominent at the eastern margins of the oceans and at the equator, where divergence of wind-driven surface currents brings nutrient-rich water from intermediate depths to the surface. Seasonally high productivity can also be found at higher latitudes due to the seasonal breakdown of upper water stratification in winter and to deep convective mixing.

It is probably safe to say that every element of the periodic table, every isotope, and an assortment of specific organic molecules that survive sediment burial have some potential for providing information on how past oceans operated. It is for us to discover the processes that regulate their distribution in the sediment, how well the chemical signals are preserved during burial, and whether they can then be used to infer past changes in the processes that generated them. Often, a specific element or isotope is affected not only by one but by several oceanic processes. Different elements can also be affected by the same processes, but with a somewhat different response.

Decoding this chemical message is rather like solving a jigsaw puzzle in which each piece is a puzzle in itself. You first have to build the pieces of the overarching puzzle one at a time—that is, you try to develop proxies for oceanic processes that you think may play an important role in climate control. As you keep building new pieces, you make preliminary tests to see how they come together. Oftentimes, you find that some pieces don't quite fit and need to be adjusted. Sometimes several pieces will fit nicely together until an additional piece discloses that this was just an illusion. On good days, the added information allows you to rearrange the pieces into a more convincing pattern. On bad days, the whole thing falls apart and you are back to square one. Actually, you never go back to square one, even on very bad days, as a lot is learned from failures as well. This process, which is typical for many scientific endeavors, sounds rather daunting, at least in the initial stages, but as it gains momentum (and we have now reached this exciting part in our game), the overall picture becomes gradually clearer, and there is an inherent synergism in the process so that the emerging picture itself is giving you hints on how to build important missing pieces or rearrange those that don't quite fit.

There is a good illustration of this process in the ongoing development of paleoceanographic tools that use natural radioisotopes formed in seawater from the decay of dissolved uranium. In view of the recognized importance of the biological pump in reducing atmospheric CO_2 (see article on page 4), past change in ocean productivity is an obvious part of the "puzzle" for which a "piece" needs to be "built." Different approaches are being explored to reconstruct that important characteristic of past

Figure 3: Uranium decay series: U-238 initiates a decay series that produces thorium 230, while U-235 produces protactinium 231.



Jayne Doucette

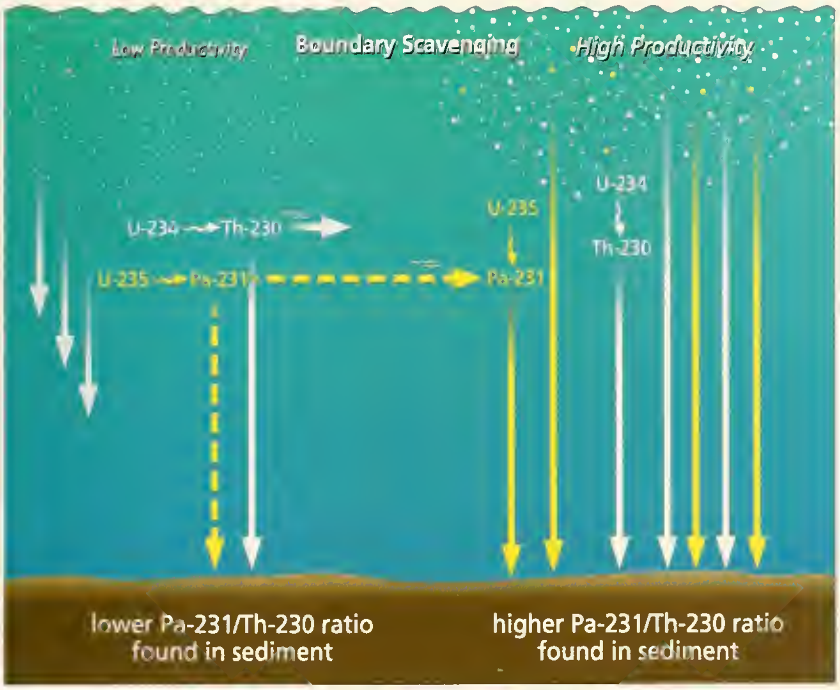


Figure 4: Boundary scavenging. Thorium 230 is rapidly scavenged, that is, adsorbed onto settling particles and removed to the underlying sediments, shortly after its formation from the decay of U-234. Because of its short residence time in the water column, very little thorium 230 can be transported laterally before removal from seawater. Protactinium 231 is less rapidly scavenged from the water column and is laterally transported towards regions of higher productivity where particle settling flux and scavenging rates are higher. As a result, the ratio of protactinium 231 to thorium 230 in sediments underlying more productive regions is higher than in sediments underlying less productive regions.

oceans. Ideally, one would want a synoptic (snapshot) view of past ocean productivity, similar to what satellite data offers for the modern ocean. In one of these approaches, paleoceanographers are attempting to make use of the contrasting behavior of the two natural radionuclides thorium 230 and protactinium 231.

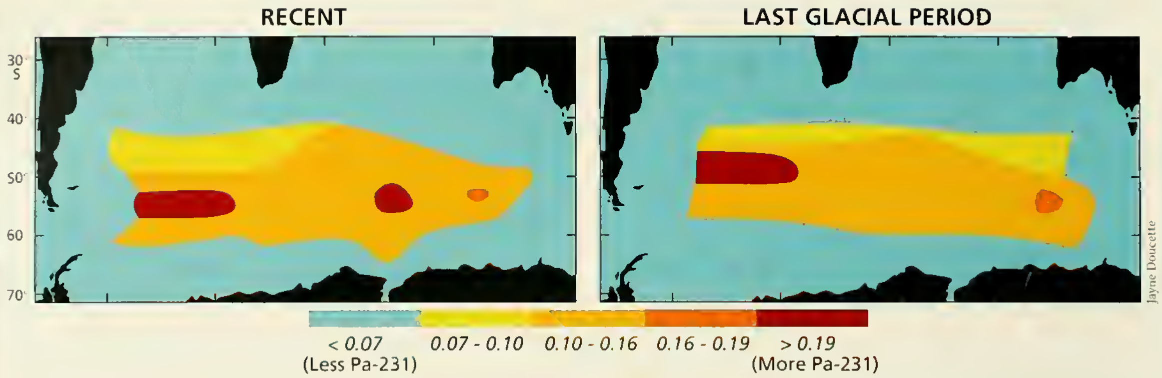
Weathering removes uranium from crustal rocks and rivers transport it to the ocean, which has a uniform uranium concentration everywhere. Two primary uranium (U) isotopes, U-238 and U-235, initiate different decay series and produce daughters with distinct properties (Fig. 3). Among these daughters, thorium 230 (Th-230) and protactinium 231 (Pa-231) are particularly useful for late Quaternary paleoceanography. Unlike their parent uranium isotopes, Th-230 and Pa-231 are very insoluble in seawater. They are rapidly adsorbed onto settling particles and removed to the underlying sediments through a process called "scavenging." Such particle-reactive isotopes can be removed directly to the underlying sediment, or they can be transported laterally with seawater to be removed in regions of higher particle flux where the rate of scavenging is higher (Fig. 4). Partitioning between these two removal pathways depends on the residence time of the insoluble element in the water column. Of the two, Th-230 is the most particle-reactive. It resides in the water column for a very short period before removal, so there is very little time available for its lateral transport. Th-230 is, then, primarily removed to the sediment underlying the region where it is produced. In contrast, Pa-231 is less particle reactive and resides in the water column long enough for lateral transport over substantial distances before removal. As a result, a significant fraction of the Pa-231 produced in low productivity, low export flux regions is removed to the sediment underlying more productive regions with high export flux (Fig. 4). Sediments underlying productive regions should thus have a high Pa-231/Th-230 ratio, while those underlying low productivity regions should have a low ratio.

The validity of this model was checked by analyzing surface sediments and comparing the results to productivity maps of the modern ocean. We first looked at the Pacific Ocean, where the distribution of Pa-231/Th-230 in surface sediments compares very well with satellite imagery of ocean color and productivity (Fig. 5). Next we reconstructed export production during the last glacial period in the southern ocean (the seas around Antarctica). Comparing the distribution of Pa-231/Th-230 in modern and glacial sediments (Fig. 6) suggests that while there was relatively little change in the total productivity of the southern ocean, there was a clear northward migration of the belt of high values (and presumably high production), which is most apparent in the Atlantic sector. However, while the distribution of Pa-231/Th-230 in modern sediments again fits expectations reasonably well, the conspicuous maxima imprinted in the sediment are not as pronounced in satellite imagery. We now know that Pa-231/Th-230 in settling particles can also be significantly affected by the abundance of biogenic opal, which has a high affinity for protactinium. This piece of the "puzzle" will thus have to be adjusted accordingly. The reason this problem does not occur in the equatorial Pacific is that opal content is comparatively low in this region.

A more substantial but constructive readjustment resulted from measurement of the Pa-231/Th-230 ratio in Atlantic sediment. Just as in the Pacific,

Figure 5: The protactinium 231 to thorium 230 ratio in surface sediments in the eastern equatorial Pacific. Compare the color pattern with that of area A in the top figure opposite.

Figure 6: The protactinium 231 to thorium 230 ratio in recent sediments deposited in the Atlantic and Indian Ocean sectors of the southern ocean around Antarctica (compare the color pattern to area B in Fig. 2) and in sediments deposited during the last glacial period.



export production is high in the eastern equatorial upwelling region (Fig. 2). We expected to find very high Pa-231/Th-230 in this region and much lower values in the central open ocean. Instead, however, low values were invariably found throughout the Atlantic, with only a few marginally higher values off West Africa (Fig. 7). This finding, surprising at first, brought to the fore the importance of an additional variable that had been largely neglected in previous work. The Pa-231/Th-230 ratio depends not only on the particle flux and scavenging intensity, but also on the rate of Pa-231 transport by currents moving from low flux to high flux regions (Fig. 4). A water mass called the North Atlantic Deep Water is produced by cooling in the North Atlantic, where it sinks before flowing southward to mix with the circumpolar deep water around Antarctica. As a result of this water entrainment, much of the Pa-231 produced in North Atlantic Deep Water as it transits the Atlantic is flushed into the southern ocean, and very little can accumulate in the Atlantic's high productivity regions.

While it complicates the interpretation of sedimentary Pa-231/Th-230 in terms of export production, this finding also provides a means of constraining past changes in the rate of thermohaline circulation, another important piece of the atmospheric CO_2 "puzzle." This approach was actually used to establish that thermohaline circulation was as vigorous during the last glacial period as it is today. The Pa-231/Th-230 ratio is still useful to constrain export production, but exchange of Pa-231 between ocean basins must be taken into account. Other paleoproductivity proxies, based on different principles and biased by oceanic processes other than circulation, are also being developed. By combining these different approaches, we better document and quantify glacial productivity. In turn, better glacial productivity estimates will allow us to better constrain thermohaline circulation rates from the distribution of Pa-231/Th-230.

Such iterative improvements of complementary proxies for related oceanic processes gradually lead us to an increasingly refined understanding of the mode of operation of past oceans and its influence on climate. Moreover, the paleoceanographic perspective that is being generated also provides important new insights into the working of the modern ocean and improves our forecasting ability for the future.

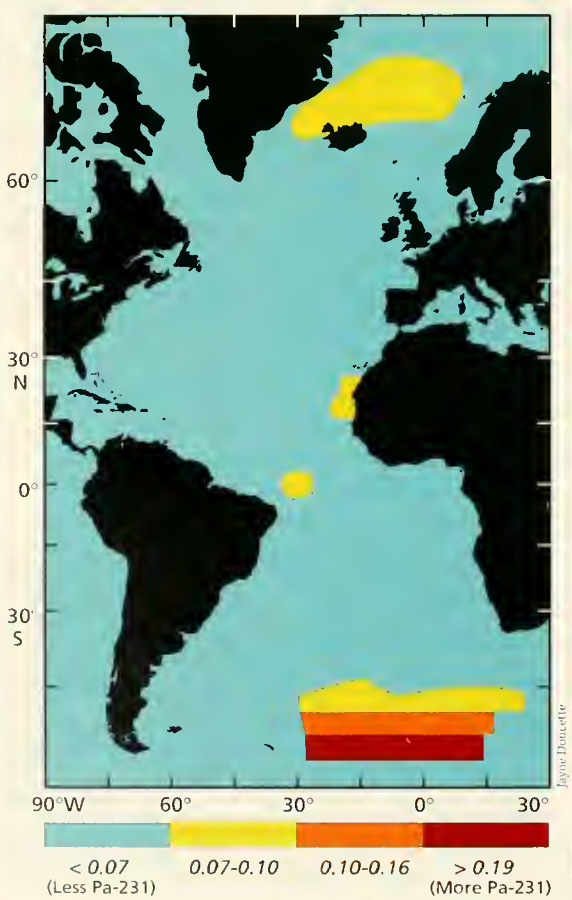


Figure 7: The protactinium 231 to thorium 230 ratio in Atlantic Ocean surface sediments.

Funding for research described in this article was provided by the National Science Foundation.

Roger François started his career as a textile engineer in Zaire, printing faux-batiks on the shores of Lake Tanganyika. Looking for a more exotic occupation, he moved to Vancouver to learn the trades of oceanography and ski mountaineering, when he noticed that he was prone to being seasick and was afraid of heights. Receiving better reviews for his oceanographic accomplishments than for his telemark turns, he moved to Woods Hole to become a full-time oceanographer.

An MIT/WHOI Joint Program graduate, Mike Bacon has been on the WHOI Scientific Staff since 1977. He specializes in the use of uranium-series nuclides to study ocean processes. In his spare time he also enjoys active participation in the education of his six-year-old daughter Alexandra. Mike also enjoys studying and trading the financial markets, where he says he is still hopeful of eventually making a profit.

Jim Price (left) and Jim Valdes with a prototype of the neutrally buoyant sediment trap. The four small plastic tubes collect sediment and the large central tube houses electronics, a variable displacement device, recovery beacons, and batteries.

Tom Kleindinst

A New Way to Catch the Rain

James R. Valdes
Senior Engineer, Physical Oceanography Department
Ken O. Buesseler
Associate Scientist, Marine Chemistry and Geochemistry Department
James F. Price
Senior Scientist, Physical Oceanography Department

The carbon budget of the upper ocean includes an important loss to the deep ocean due to a very slowly falling rain of organic particles, usually called sediment. As this sediment falls through the upper water column it is consumed, mainly by bacteria, and the carbon is recycled into nonsinking forms (dissolved or colloidal organic carbon or inorganic forms). Thus the sediment rain decreases with increasing depth in the water column, and only a tiny fraction reaches the deep sea floor, less than about one percent.

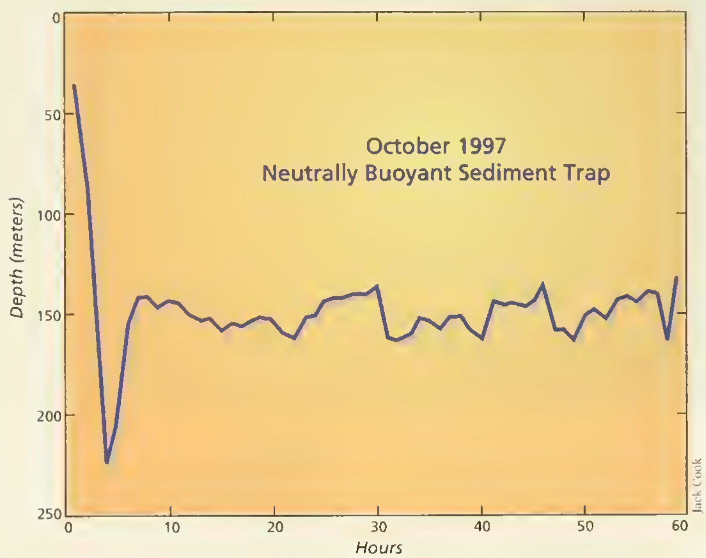
It is of great interest to observe the sediment rain at different depths in the ocean so that the recycling rate can be quantified. There is a long (and contentious) history of sample collection in simple, open-topped cylinders or "traps." For reasons of technical convenience, these traps have been either attached to moorings or tethered from surface floats. The ongoing Bermuda Atlantic Time Series (BATS)* program utilizes surface-tethered traps to catch sediment falling through the upper 300 meters of the ocean. These traps are deployed for three to five days during the regular monthly BATS cruises, and the contents are then analyzed for the carbon,

*BATS is a US Global Ocean Flux Study time-series program operated from the Bermuda Biological Station for Research. It was sited to take advantage of the nearby OFP site (see article on page 15) and Station S, a hydrological station initiated under the banner of the 1957–58 International Geophysical Year (see *Oceanus* Vol. 39, No. 2 for an article on Station S).

nitrogen, and other elements being carried to the deep ocean by the sediment rain. BATS investigators, especially Tony Michaels, now at the University of Southern California's Wrigley Institute, who first interested us in this problem, have been unable to close the upper ocean carbon budget using these data. It seems that on annual average, there is an unaccounted loss in the carbon budget. Perhaps there is an important unknown process acting to deplete the upper ocean carbon budget, or perhaps the surface-tethered sediment traps may be undercollecting the sediment. The former would be the most exciting result, but there is good reason to suspect a role for collection error, and that is what we have begun to address.

A collection error by a moored or a surface-tethered sediment trap is easy to imagine; the sediment falls through the water at a rate of about 10 to 200 meters per day, while it is carried horizontally by currents at a rate of from 5 to 50 kilometers per day (typical of currents in the upper ocean—deep ocean currents may be much less). A fixed or surface-tethered trap will thus be immersed in a nearly horizontal flux of sediment. Flow past the trap would set up vortices that could either enhance or reduce the collection of sediment, depending upon the fall speed of the sediment, the speed of the current, and the tilt and geometry of the trap. Similar collection problems are known to afflict most rain gauges (we mean water rain!), and the phenomenon can be reproduced and studied in controlled, laboratory experiments. But even if we knew in great detail the dynamics of this collection error, we could not apply this knowledge to correct the presently measured sediment flux since the currents and the sediment falling speeds are highly variable and, in practice, not easily measured.

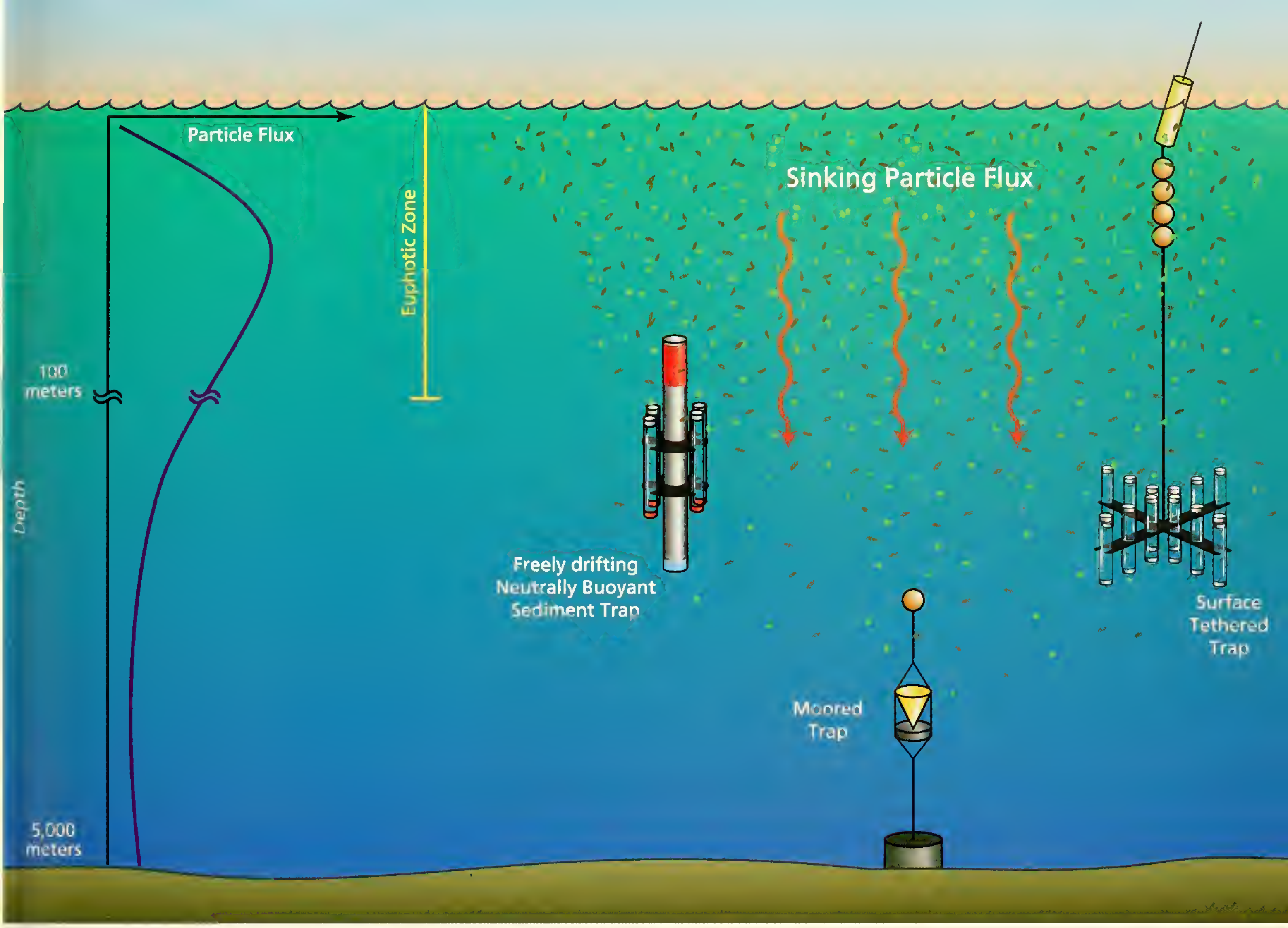
An obvious solution is to make a sediment trap that drifts freely with the currents, so that the flow past the trap is effectively zero (imagine the wind blowing past a hot air balloon). Based upon this idea, and armed with a grant from the Green Foundation, we have developed and recently begun to test a new sediment trap that we call the Neutrally Buoyant Sediment Trap (NBST). The NBST is built from components and techniques familiar to us from our work with a variety of neutrally buoyant float systems. The main challenge for the NBST was to float at a prescribed depth, with shallower depths, 150 to 300 meters, being the most difficult. Around Bermuda, where we have started NBST testing, the ocean is very weakly stratified at these depths, and thus the ballasting of an NBST becomes extraordinarily sensitive. An error of just one gram in the weight of a 16 kilogram instrument leads to a depth error of about 40 meters, which is unacceptable. The NBST traps also carry a significant load of denser water (an unpleasant solution of saline and formaldehyde to preserve the samples and discourage theft by midwater scavengers, mainly small shrimp) that can be partially flushed out during launch. To overcome these ballasting issues we decided to endow the NBST with a variable displacment device (a cylinder and piston in contact with the sea) and a very modest brain, or microprocessor, so that it could be self-ballasting. Thus the NBST measures pressure, and if it finds that it is deeper, say, than its target depth, then it increases its displacement by forcing the piston outwards, something like a miniature submarine blowing ballast. By repeated checking and correcting at hourly intervals, the NBST can be made to float at a prescribed depth almost anywhere in the water column.



A record of pressure measured by a neutrally buoyant sediment trap during a three day-long deployment. The trap is passive for the first three hours after launch, and then begins to check and correct depth at hourly intervals. This instrument was targeted for 150 meters depth, and was slightly heavy as it was launched. At hour four it rose to the target depth by increasing its displacement slightly. It then remained within about 10 meters of its target depth until the end of its mission.

While the NBST idea is inherently simple, it still happens that testing the prototype NBSTs at sea has been hair raising, since they are autonomous and not command-recoverable once they are launched. On our first field test in summer 1996 we deployed a glass-hulled instrument (glass has several important advantages as a hull material, including being able to endure very high pressures). Unfortunately, the sea state was high at the time of deployment, and we bumped the NBST with the ship. This cracked the hull, and led to a prompt sinking (we now make the hulls from aluminum tubing that is better able to take such abuse). On a later trial we lost two out of two instruments due, we think, to electrical interference between a new high voltage light, intended to be used as a recovery beacon, and the microprocessor (we have redesigned the light).

These failures were a loss of time and resources, and they were also intensely disappointing. But we



were confident that our basic idea had merit, and we persisted in building and deploying NBST prototypes until finally achieving real success during this past summer and fall. With assistance from Debbie Steinberg and co-workers at the Bermuda Biological Station for Research, we obtained our first NBST samples during the summer of 1997. During this test an NBST at 150 meters collected approximately the same sediment flux as a surface-tethered trap at the same depth; however, a second NBST at 250 meters depth collected significantly more material than the comparable surface-tethered trap. Thus the profile of the sediment flux, which is a direct consequence of the recycling process, appears very different when measured by an NBST compared with conventional traps (the NBST-measured flux appears to fall off less rapidly with depth). On still another successful deployment this past fall, an NBST at 150 meters collected significantly less material than did a comparable surface-tethered trap, and we found that the kind and quality of the collected material was markedly different.

Our story of upper ocean sediment trapping is still unfolding, but we can already see that it will not be as straightforward as a simple under- or over-collection error. If indeed there is a collection error by surface-tethered traps (and there probably is, given our results to date), then it likely depends upon the season, since the kind of material that makes up the sediment flux changes with season, and also with depth. During the next two years we hope to make a series of comparisons over a full annual cycle as part of the BATS program. These new data are sure to spark a great deal of interest among the geochemists who have grappled with these difficult problems, and it may, perhaps, inspire other engineers to conceive still better means to measure this very gentle but crucially important rain of organic material that falls through the upper oceans.

The authors are grateful to the Green Foundation for a technology development grant that made their floating sediment trap project possible.

Authors Valdes, Buesseler, and Price collectively have 58 years of service to WHOI science (23, 17, and 18 years, respectively), including many months at sea for each. Buesseler, who is a 1987 graduate of the MIT/WHOI Joint Program is currently in Arlington, VA, at the National Science Foundation, where he is Associate Program Director in Chemical Oceanography.

Particle flux scientists employ three main sediment trap designs. The cylindrical, surface-tethered and free-drifting neutrally buoyant traps serve in shallow waters, and the moored conical traps are used for deep waters (drawings are not to scale). Given the generally decreased particle flux at great depths (see graph at left in the figure), the deep traps' conical shape increases the collection area—these traps have a 300 times larger collection area than the shallow water traps.

Extreme Trapping

One of oceanography's major challenges is collection of data from extraordinarily difficult environments. For those who use sediments traps, two examples of difficult environments are the deepest oceans and the permanently ice-covered Arctic Basin.

Since 1986, Yoshi Nozaki (University of Tokyo) has deployed time-series sediment trap moorings in the Japan Trench where the bottom depth exceeds 9 kilometers. Despite extreme water pressure on the instruments at the deepest trap (8.8 kilometers), Nozaki has successfully redeployed the mooring many times to collect multi-year samples from this enormous depth. The water column at this location, nearly three times longer than in most of the deep ocean, provides an excellent natural laboratory for understanding, on an expanded scale, the chemical reactions at work on settling particles. Nozaki's work also concerns the broad-scale problem of Earth's carbon cycle: The Pacific plate oceanic crust at the bottom of the trench is destined to be subducted beneath the continental crust of adjacent plates. Thus ocean surface life forms contribute to the planet's carbon cycle both in the short-term when respiring carbon dioxide into the atmosphere and in the long-term (hundreds of millions of years) when, following a long trip to the deep seafloor, the carbon of their dead bodies is absorbed into Earth's crust by the plate tectonic process.

Susumu Honjo

Yoshi Nozaki of the University of Tokyo poses with one of the traps he sends nearly nine kilometers deep.

The WHOI PARFLUX group has collaborated over the last decade with the Japan Marine Science and Technology Center (JAMSTEC) to develop Ice-Ocean Environmental Buoys (IOEBs) for deployment in the Arctic. The buoys carry sediment traps to collect descending particles as well as many sensors to detect the variability of atmosphere, ice, and upper ocean layers. A field team led by WHOI Research Associate Rick Krishfield and Kiyoshi Hatakeyama of JAMSTEC fly their gear to an ice island in the Arctic Ocean by ski-equipped cargo plane. They employ a steam auger to cut a hole in the ice and then lower first the anchor, a current meter, and the sediment trap, which together form the lower portion of the mooring, followed by instruments situated farther up the line, and finally the buoy that plugs the hole in the ice. The sediment trap is programmed to open and close every half month.

An ice island slowly describes a circle within the Canadian Basin where the present IOEB study is concentrated. This experiment allows scientists to sample settling particles and make other measurements throughout a wide area over a year or longer without themselves being present during the harsh Arctic winter. The first long-term (one-year), high-resolution, time-series samples have arrived at WHOI, and we expect their analysis will contribute a great deal to our knowledge about how the biological pump operates under the Arctic ice.

—*Susumu Honjo*

(See *Oceanus* Vol. 37, No. 2 for further information on the Ice-Ocean Environmental Buoy)

Susumu Honjo

From left, John Kemp, Rick Krishfield, and Kiyoshi Hatakeyama deploy a time-series sediment trap through a hole they've drilled in the Arctic Ocean ice cover.

Crew and scientists aboard R/V *Thomas G. Thompson* (University of Washington) ready a long line of mooring flotation for launch during the Joint Global Ocean Flux Study experiment in the Arabian Sea in 1995.

THE SCIENTIFIC PROCESS & EXCITEMENT

"Decoding this...message is rather like solving a jigsaw puzzle in which each piece is a puzzle in itself. You first have to build the pieces of the overarching puzzle one at a time—that is, you try to develop proxies for oceanic processes that you think may play an important role in climate control. As you keep building new pieces, you make preliminary tests to see how they come together. Oftentimes, you find that some pieces don't quite fit and need to be adjusted. Sometimes several pieces will fit nicely together until an additional piece discloses that this was just an illusion. On good days, the added information allows you to rearrange the pieces into a more convincing pattern. On bad days, the whole thing falls apart and you are back to square one. Actually, you never go back to square one, even on very bad days, as a lot is learned from failures as well. This process, which is typical for many scientific endeavors, sounds rather daunting, at least in the initial stages, but as it gains momentum (and we have now reached this exciting part in our game), the overall picture becomes gradually clearer, and there is an inherent synergism in the process so that the emerging picture itself is giving you hints on how to build important missing pieces or rearrange those that don't quite fit."

—Roger François and Mike Bacon, *Geochemical Archives*, Page 29

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